Assessment, Prediction and Enhancement of the Reliability of Extrusion Dies

by

Mohammed Asif

A Thesis Presented to the

FACULTY OF THE COLLEGE OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

In

MECHANICAL ENGINEERING

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KING FAHD UNIVERSITY OF PETROLEUM AND MINERALS

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Date: 10/3/96

Dedicated to

my Parents

&

my Brothers and Sister

whose prayers, guidance, and inspiration led to

this accomplishment

Acknowledgment

In the name of Allah, Most Gracious, Most Merciful. Read in the name of thy Lord and Cherisher, Who created. Created man from a {*leech-like*} clot. Read and thy Lord is Most Bountiful. He Who taught {the use of} the pen. Taught man that which he knew not. Nay, but man doth transgress all bounds. In that he looketh upon himself as self-sufficient. Verily, to thy Lord is the return {of all}.

(The Holy Quran, Surah 96)

First and foremost, all praise to Allah, *subhanahu-wa-ta'ala*, the Almighty, Who gave me an opportunity, courage and patience to carry out this work. I feel privileged to glorify His name in the sincerest way through this small accomplishment. I seek His mercy, favor, and forgiveness. And I ask Him to accept my little effort. May He, *subhanahu-wa-ta-Aaala*, guide us and the whole humanity to the right path *(Aameen)*.

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I express my sincere appreciation and indebtness to my academic advisor and my thesis committee chairman, Dr. Anwar. K. Sheikh, for his constant guidance, support and help. I acknowledge him for his valuable time, encouragement and guidance during various stages of this work and my M.S studies. Working with him was indeed a learning experience.

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Nomenclature

K_{1c}	Fracture toughness of die material(Mode I)
a_i	Initial crack length
a_f	Final crack length
σ	Nominal stress at crack tip
α	Crack geometry and material parameter
ΔK	Range of stress intensity factor
C, m	Constants of the Paris equation
$\Delta\sigma_r$	Nominal stress range
R	Stress ratio
N_f	Number of cycles to failure
R_e	Reduction ratio
d_o	Initial diameter of the billet
d_1	Extruded material diameter
ϵ	Strain
σ_t	Tangential stress
σ_r	Radial stress
σ_{fm}	Mean flow stress
κ	Strength co-efficient in cold working

n	Strain hardening exponent
Q_e	Extrusion ram pressure factor
F_e	Extrusion force
p_e	Extrusion pressure
A	Strenght co-efficient in hot working
p	Strain rate sensitivity exponent
p_t	Actual extrusion pressure
μ	Co-efficient of friction
α_a	Semi die angle
r	Reduction ratio
σ_x	Drawing stress
β	Shape parameter of the Weibull distribution
η	Scale parameter of the Weibull distribution
τ_i	Shear strength at the interface
l	Length of the billet at the point of the stroke
r_i	Inner radius of the die
r_o	Outer radius of the die
v	Ram speed
$\mu(I)$	Mean of the Normally distributed input variable
$\sigma(I)$	Standard deviation of the Normally distributed I.V.

μ_l	Mean of Log-Normally distributed I.V.
σ_l	Standard deviation of Log-Normally distributed I.V.
$Z(I)$	Uniformly generated random numbers
P_s	Shearing force
σ_s	Pressure exerted on the die inner surface
A_o	Initial cross-sectional area
A_1	Final cross-sectional area
$\dot{\epsilon}$	Strain rate
$\bar{\dot{\epsilon}}$	Mean strain rate
σ_{max}	Maximum stress
σ_{min}	Minimum stress
σ_m	Mean stress
$\overline{\overline{T}}$	Average die life
CCD	Circumscribing circle diameter
t_{min}	Minimum wall thickness of the profile
$R(t)$	Reliability function
$F(t)$	Cumulative distribution function
$f(t)$	Probability density function
$\lambda(t)$	Failure rate
K_{th}	Threshold stress intensity value

V	Instantaneous ram velocity
h	Ram displacement
$D(t)$	Depth of wear at time t
$\alpha(t)$	Extreme Value Distribution parameter
$\mu_{D(t)}$	Mode of the distribution of largest wear depth
$\sigma D(t)$	Standard deviation of the deepest wear at time t
$D^{*}(t)$	Critical wear depth
t_f	Time to failiure: die failed due to fracture
t_w	Time to failiure: die failed due to wear

Abstract

Name: **Mohammed Asif**

Title: **Assessment, Prediction and Enhancement of the Reliability of Extrusion Dies.**

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The die life data from a large aluminum extrusion plant is comprehensively analyzed. to determine the nature of the reliability model suitable to characterize the data. It is shown that the extrusion die life corresponding to all modes of failures can be modeled by Weibull reliability model. Since fracture and wear are the two main modes of die failure. they are also treated separately. A fracture mechanics based model is proposed to predict the life of dies failed due to fracture, using Monte Carlo Simulation. Another wear based simulation model is also developed to predict the life of dies failed due to wear. Finally a competitive risk model is formulated to model the real situation when both of these major causes of failure are present simultaneously. Comparison of the simulated results is made with the real life data collected from a local extrusion plant (ALUPCO). and the validity of weibull model for the die life prediction is established. One of the objective of the work was to correlate the mean and scatter of the die life (or the scale and shape parameter of the weibull model) with the profile complexity of the die. Die complexity definition in literature was found to be inadequate, and a new die complexity definition was proposed which was based on multiple regression analysis of average die life . and key variables, and parameters having a major influence on the die life. Thus in the absence of any historical die life data, the die reliability can directly be predicted using the proposed die complexity and die life correlation. Using the results of this study it will be possible to calculate the number of dies required to meet a production target (corresponding to specific die reliability requirement). to make a comparative assessment of dies, as well as to determine the age replacement strategies for the die.

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ملخص الرسالة

الإسم : محمد آصف
العنوان : تقرير، تنبؤ وتحسين الإعتمادية لإسطنبات التشكيل بالبثق
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تم تحليل شامل للمعلومات الخاصة بعمر الإسطنبات في محطة كبيرة لتشكيل الألومنيوم بالبثق وذلك لتحديد طبيعة نموذج الإعتمادية المناسب لتوصيف هذه المعلومات . وقد وضح أن أسطنبة البثق المقابل لكل إشكال الإنهيار (التلف) يمكن تمثيله باستخدام نموذج وايبل للإعتمادية . ونظرا لأن الكسر والتآكل هما أكثر اشكال التلف فقد تمت دراسة منفصلة خاصة بهما . ولقد اقترح نموذج قائم على ميكانيكا الكسر وذلك للتنبؤ بعمر الإسطنبات التى تتلف بالكسر وذلك باستخدام طريقة محاكاة مونت كارلو . كما تم تطوير نموذج آخر قائم على محاكاة التآكل وذلك للتنبؤ بعمر الاسطنبات التى تتلف بالتآكل . آخيرا تم وضع نموذج لتنافس الخاطر وذلك لتمثيل الوضع الحقيقى عندما يتواجد هذان السببان الرئيسيان للتلف فى وقت واحد .

ولقد تمت مقارنة نتائج هذه النماذج مع البيانات الدقيقية لعمر الأسطنبات والتى تم الحصول عليها من محطة محلية للتشكيل بالبثق (الوبكو) ولقد تم التأكد من صلاحية نموذج وايبل للتنبؤ بعمر الإسطنبات . وهذا أحد أهداف هذا البحث هو الربط بين متوسط عمر الأسطنبة وتشتت البيانات الخاصة بعمر الاسطنبة حول هذا المتوسط (أو المقياس ومعامل الشكل لنموذج وايبل) من ناحية وبين مدى تعقد شكل الأسطنبة من ناحية أخرى . ولقد وجد أن تعريف مدى تعقد شكل الأسطنبة الموجود فى الأبحاث السابقة غير كاف ولذلك تم اقتراح تعريف جديد لمدى تعقد شكل الأسطنبة ويقوم هذا التعريف الجديد على تحليل البيانات المرتبطة بمتوسط عمر الأسطنبة ويقوم هذا التعريف الجديد على تحليل البيانات المرتبطة بمتوسط عمر الأسطنبة والمعاملات والمتغيرات ذات التآثير الرئيسى على عمر الأسطنبة . وبذلك وفى غياب أى معلومات عن تاريخ الأسطنبة فإنه يمكن التنبؤ مباشرة باعتمادية الأسطنبة باستخدام العلاقة المقترحة بين مدى تعقد شكل الأسطنبة وعمرها . وباستخدام هذه الدراسة سوف يكون من الممكن حساب عدد الأسطنبات المطلوبة للقيام بهدف انتاجي محدد (بما يقابل متطلبات اعتمادية معينة للأسطنبات) كما سيكون من الممكن القيام بتقدير مقارن للأسطنبات بالإضافة إلى امكانية تحديد استراتيجيات الإحلال الزمنى للإسطنبات .

درجة الماجستير في العلوم

جامعة الملك فهد للبترول والمعادن

الظهران ، المملكة العربية السعودية

ديسمبر ١٩٩٥م

Chapter 1

Introduction

This thesis comprises basically of a comprehensive study of extrusion die performance in a typical Aluminum extrusion plant. Die life plays a central role in determining the overall economics of the extrusion process. Quality and reliability of dies also have a major impact on the quality of the product extruded. Die life estimation and its enhancement, as well as its implications on the quality of the product are the major areas of interest in extrusion industry.

In the current competitive environment the flexibility and in time delivery are the two important factors for the success in the aluminum extrusion business. Improved competitiveness often requires a decreased time between getting an order and the delivery of the finished: extruded profile. Hence, just by getting the profile shape drawing, the process engineer should be able to evaluate the required number of dies through the complexity of the shape and thus optimize the cost of the over all process.

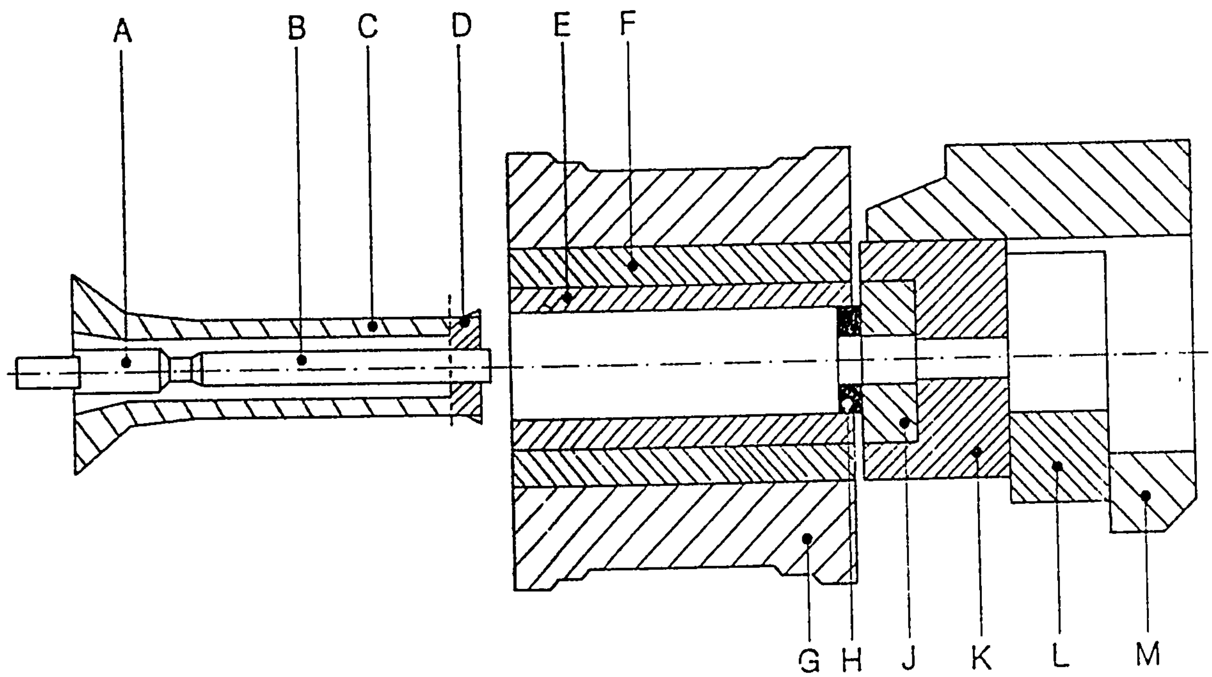
Aluminum is probably the most ideal metal for extrusion and is the most commonly extruded. Most commercially available aluminum alloys can be extruded. Depending on the alloy, billet temperatures generally range from about 575 to 1100°F (300 to 600°C). Major applications include pipes, wire, rods, bars, tubes, hollow shapes, cable sheathing, architectural and structural sections, and automotive trims. Most sections are extruded from heat-treatable, high strength aluminum alloys [1].

1.1 Extrusion

Extrusion is the plastic deformation in which material is forced under pressure to flow through one or more die orifices to produce products of the desired configuration. In hot extrusion, heated billets are reduced in size and forced to flow through dies to form products of uniform cross section along their lengths, with special tooling, stepped and tapered extrusions are produced. The temperature at which extrusion is performed depends on the material being extruded (for aluminum alloys the temperature range is from 300°C-600°C). Most commercially available aluminum alloys can be extruded into practically any intricate shape to meet almost any design requirement. In non-lubricated hot extrusion for aluminum, the material flows by internal shear, and a dead metal zone is formed in front of the extrusion die. It is relatively straight forward process once the condition has been defined. However, a large number of metallurgical and processing factors interact and affect the mechanical properties, surface finish and corrosion resistance of the final product. The advantages of hot extrusion process include improving the microstructure and physical properties of the material. maintaining close tolerances. material conservation, economical production. and increased design flexibility.

A typical extrusion die assembly is shown in Fig. 1.1 and the sequence of operations for the forward extrusion process are as follows:

- The heated billet and the dummy block are loaded into the container.
- The billet is extruded by the force of the ram being pushed against it. this upsets the billet. then forces the metal to flow through the die. During extrusion. a thin shell of material may be left on the container wall. Extrusion is halted in order to remove a thin disk of material (butt) in the container.
- The container is separated from the die. the extruded section with the butt. and dummy block.
- The discard butt is sheared off.
- The shear (flat-face) die, the container. and the ram are returned to their initial (loading) positions.
- A new billet is again put into the container which is welded to the remainder of the previous billet under ram pressure, this welded region appears as a defect



A. Mandrel Holder
B. Mandrel
C. Stem
D. Dummy Block
E. Liner
F. Intermediate Liner
G. Mantle
H. Die
J. Die Ring
K. Bolster
L. Wedge Block
M. Die Head

Figure 1.1: Extrusion Die Assembly.

on the extruded profile and is sheared off and discarded, when the extruded section is cut into order lengths.

The emerging section is cooled and guided along a moving run-out table before being cut into production lengths up to 40 meters. The lengths are then given a controlled stretch for straightening, and are then cut to finish order lengths. A final precipitation or ageing heat treatment is applied to alloys to complete the production process.

The load in forward extrusion initially increases very rapidly as the billet upsets to fill the container. This is followed by a further increase in pressure, and extrusion begins. A somewhat cone-shaped deformation zone then develops in front of the die aperture. After the maximum load has been reached, the extrusion pressure falls as the billet length decreases until a minimum is reached, then rapidly increases again. This last pressure increase occurs because only a disk of the billet remains and the metal must flow radially toward the die aperture. Resistance to deformation increases considerably with decreasing thickness. Each billet cycle constitutes a stress or fatigue cycle as seen in Fig. 1.2

The life of an extrusion die is the duration up till which, it performs satisfactorily in terms of the quality of the product being extruded.Hence if lines appear on the extruded product surface or the die cavity wears out of tolerance rendering unacceptable weight/length of the product, the die is considered failed. The life of a die can be expressed in a no. of ways:

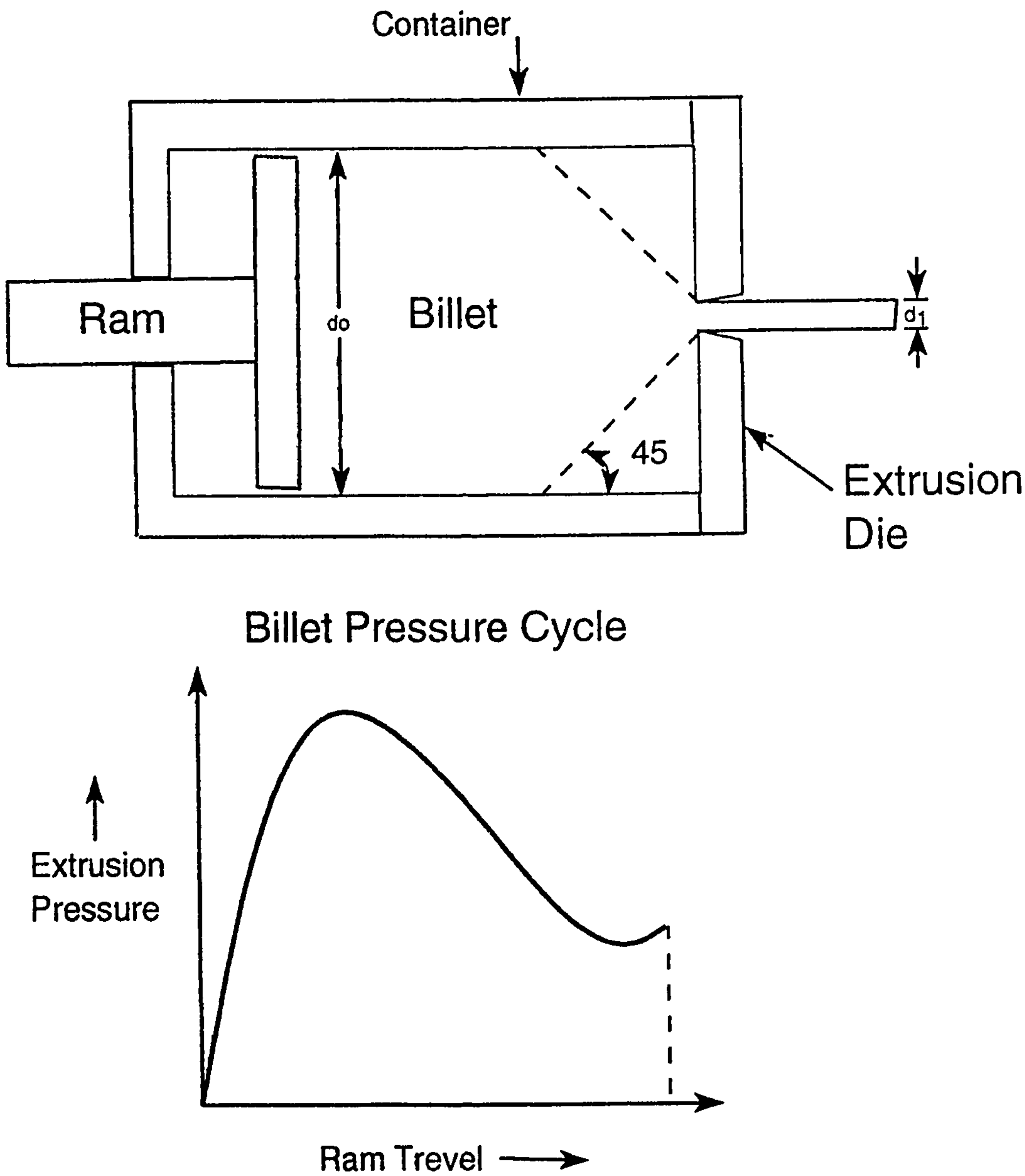


Figure 1.2: Extrusion Pressure Cycle.

- Number of pushes or number of billets extruded, after which the die fails.

- It can also be expressed in terms of the total weight of metal extruded (kg).

$$\text{Total Weight} = (\text{No. of Pushes}) * (\text{Wt. of a billet})$$

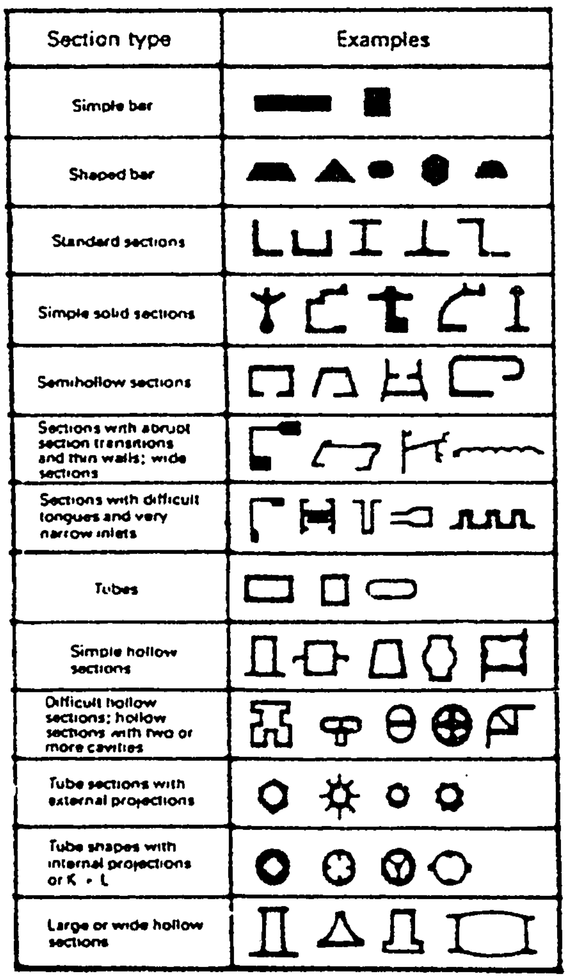
The characterization of die life based on total weight of metal extruded through a die will be used in this work.

Extruded sections can be hollow or solid, thick or thin, of simple or intricate shape, and of any size with in the capacity of the press. A few examples of the aluminum extrusions are illustrated in Fig. 1.3.

Some shapes which cannot be rolled because of their geometry (such as those with reentrant angles) can be readily extruded. Also, some alloys which cannot be hot rolled because of a severe decrease in temperature during rolling can sometimes be extruded. Other alloys which fracture when deformed unless they are contained on all sides can be extruded more readily than they can be rolled.

The size of an extrusion is measured by the diameter of the smallest circle that will enclose its cross-section. This is known as the *Circumscribing Circle Diameter*, CCD. Aluminum extrusion with CCD ranging from *64 to 787*mm(*1/4* to *31*″) are produced, often in lengths more than *30.5m*(*100ft*) [1].

The rapid and severe reduction of the material under high pressure in hot extrusion refines the grain structure, minimizes decarburization or coating, and usually imparts improved and uniform properties to the extruded product [2]. For many



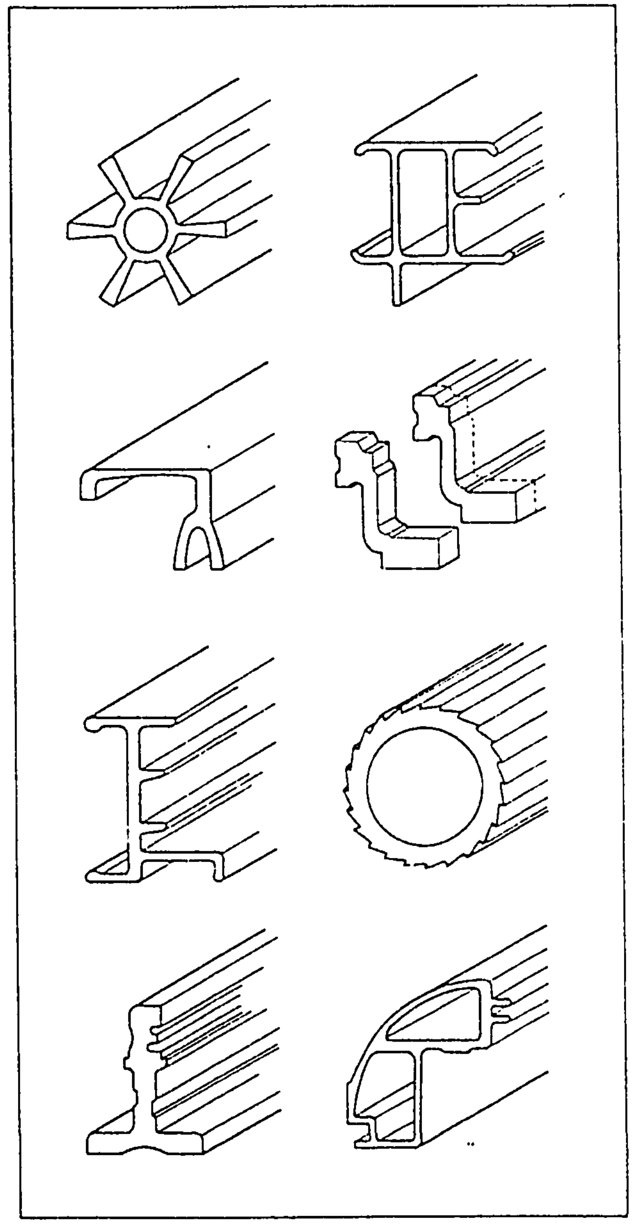


Figure 1.3: Examples of Aluminum Extrusions.

applications, the properties of the extrusion are further improved by subsequent heat-treating, ageing or cold-working processes, such as drawing. The surface finish of aluminum extrusion is generally $1.60\mu m(63\mu in)$ or less. The surface finish of steel extrusions is typically $3.175\mu m(125\mu in)$, but finishes of $1.60\mu m$ have been produced on close-tolerance extrusions of steel and titanium.

1.2 Extrusion Dies

Extrusion dies can be divided into simple ones used for solid and open shapes and those with welding chambers (porthole, spider and bridge dies) for semihollow and hollow shapes as shown in Fig. 1.4. The normal type of die for solid and open semihollow shapes can, in principle, be used for all metals that are extruded. Hollow sections in a variety of shapes and sizes are reserved for aluminum alloys apart from the simple hollow sections that can be produced in the heavy metals or steel with a mandrel. The development of die design for simple and complicated aluminum sections is described below.

1.2.1 Die Design

A die for aluminum extrusion must be able to produce or has to fulfil the following demands or requirements:

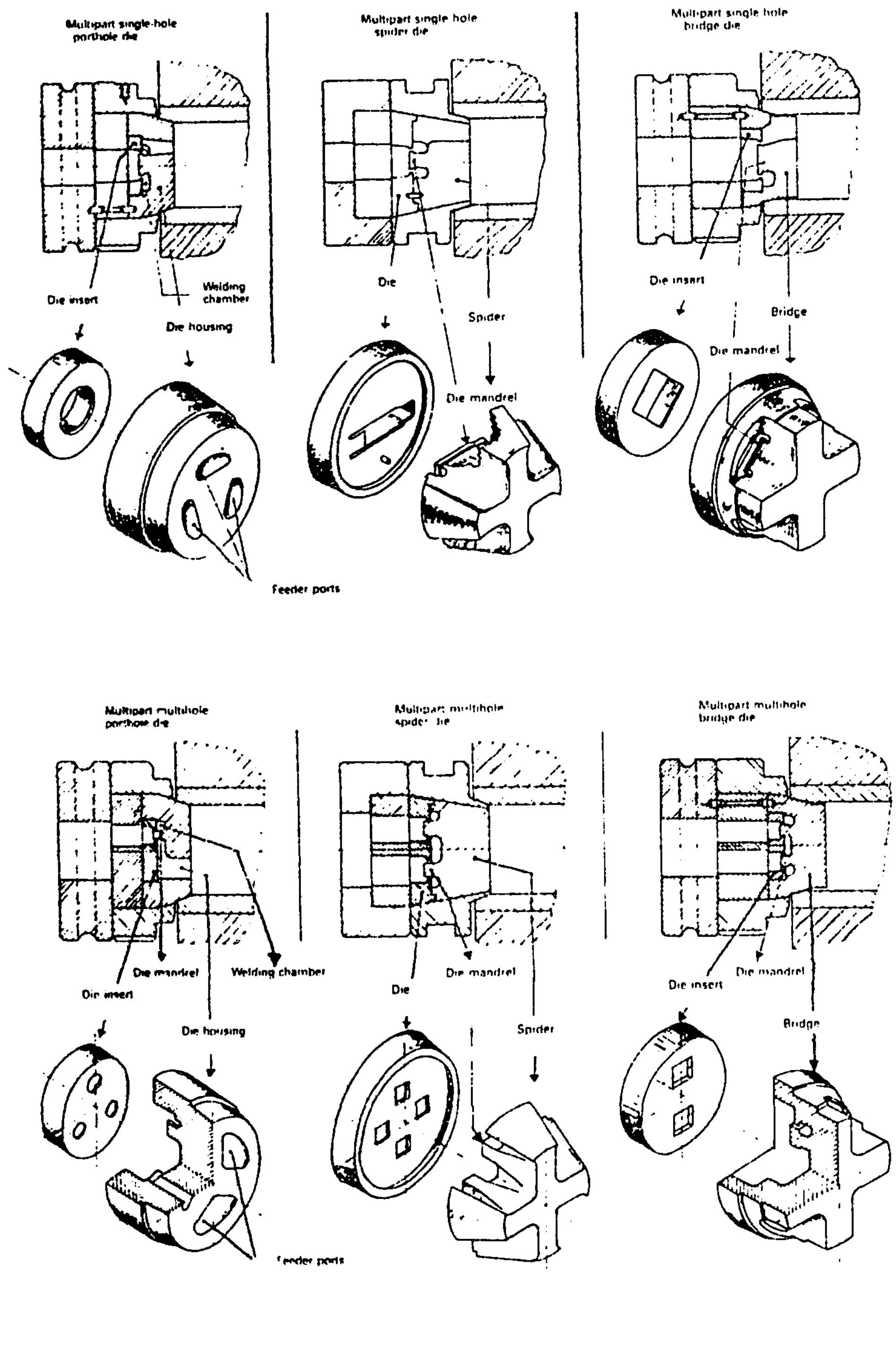


Figure 1.4: Figure showing single-hole and multihole; porthole, spider and bridge extrusion dies.

(a) Accurate dimensions and product shape, to avoid the need for any corrective work.

(b) Maximum possible working life.

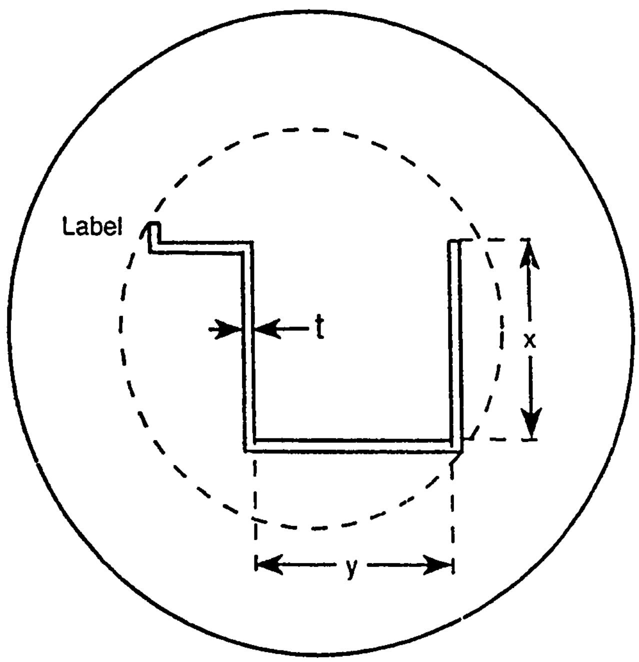
(c) Maximum length of extruded section.

(d) A good-quality surface finish maintained over many extrusions i.e. infrequent die cleaning.

(e) Good performance at high extrusion speeds.

(f) Low manufacturing costs.

These requirements are usually fulfilled with rod and simple shapes. However, as the complexity of the die increases, it becomes increasingly more difficult to comply with all the six requirements. Many factors have to be considered in the design and construction of a die, including the flow pattern, maximum specific pressure, geometrical shape of the section, wall thickness and tongue size, circumscribing circle diameter, shape of the bearing surface (die land), and the tolerance of the section. The tongue size or the tongue ratio as it is known and the circumscribing circle diameter, CCD are elaborated in Fig. 1.5. Incorrect metal flow can give rise to areas of critical deformation, which form visible streaks on the surface of the finished product.



Tongue Ratio = $(x \cdot y)/y^2$

- - - - Circumscribing Circle Diameter

t = minimum wall thickness

Figure 1.5: Figure showing the tongue ratio and the circumscribing circle diameter, CCD of a typical semi-hollow aluminum extruded die.

Successful and economical hot extrusion requires, careful consideration with respect to the design of the tooling components, selection of the materials from which they are made and method by which they are manufactured and heat treated [3]. Two common types of dies are flat-faced and shaped dies. Flat-faced die, sometimes called square or shear dies, have one or more openings (apertures) similar in cross-section to the desired extruded product. These dies are easier to design and manufacture than shaped dies, and are commonly used for the hot extrusion of aluminum, copper, brass and magnesium alloys.

In the process of aluminum extrusion, the die itself is a very critical production factor, which in many cases plays an important role, both in production economy and in business flexibility. Basically, the die material properties should provide the following desirable benefits to the extrusion process

- Good, reliable and safe die performance.

- Easy and quick die making.

The die material should have desirable characteristics of high hot hardness, toughness, wear resistance, and mechanical strength. It should provide a reasonable die life and must have a consistent performance as far as possible. More details of material aspects of extrusion dies are given in chapter 3.

Die making normally involves machining, spark erosion, heat treatment and often nitriding. Heat treatment in particular is a costly and time consuming factor. Out of the various categories of tool materials, industry have found that. H-13 steels(which are the primary focus of this study) are the most appropriate materials for extrusion dies. Their making comprise of conventional hardening as well as at least two temperings: corrections of the die are often needed due to shape changes during hardening. H-13 steels have all the desirable characteristics of strength, toughness, hardness, etc., and are relatively easy to manufacture.

Die design is a critical aspect of the extrusion process and embodies both science and art. Optimum design is influenced by many factors, including the circumscribing circle diameter of the shape to be produced, the maximum and minimum wall thickness, the press capacity, the length of the runout table, the stretcher capacity, the tool-stacking(quantity) limitations, an understanding of the properties and characteristics of the metal to be extruded, and the press operating and maintenance procedures. Since all metals shrink upon cooling after hot extrusion, a shrinkage allowance must be provided in designing the dies. Deformation of the die under high pressures and expansion resulting from high temperatures must also be considered in die design. Another important consideration is the tendency of metals to flow faster through a larger opening than a smaller one. This must be compensated-for in designing dies for extruding certain sections. For example, when a section to be extruded has both a thick wall and a thin wall, various means are employed to retard metal flow through the thick sections and increase flow rate through the thin section of the die. Fine adjustments to the die for correcting or changing the rate of metal flow are made by varying the length of the land, also called the bearing, directly behind the die opening. By decreasing the length of the bearing, the rate of flow is increased: increasing the bearing length reduces the flow rate. The geometry of the die aperture at the front and back of the bearing surface is known as the choke and relief respectively as illustrated in Fig. 1.6. If the die designer expects to encounter difficulty in filling sharp corners or completing thin sections of the extruded product, a choke may be provided on certain portions of the bearing surface. This slows the rate of metal flow and consequently fills the die aperture. Increasing the amount of back relief at the exit side of the bearing surface increases the rate of material flow.

There are various approaches to maintain the aluminum extrusion dies, but it has been established that the extrusion dies work best if subjected to a periodic, pre-planned, maintenance schedule. A schedule for such a die maintenance program can be selected according to an extrusion thickness and the number of billets pushed (target weight).

1.2.2 Die Maintenance

In an extrusion industry each die is used in a pre-planned fashion and subjected to scheduled maintenance/renitriding operations. A flow chart describing the circulation of extrusion dies in the extrusion plant according to the extrusion target weight concept is shown in Fig. 1.7 [4].

The sequence of events are as follows

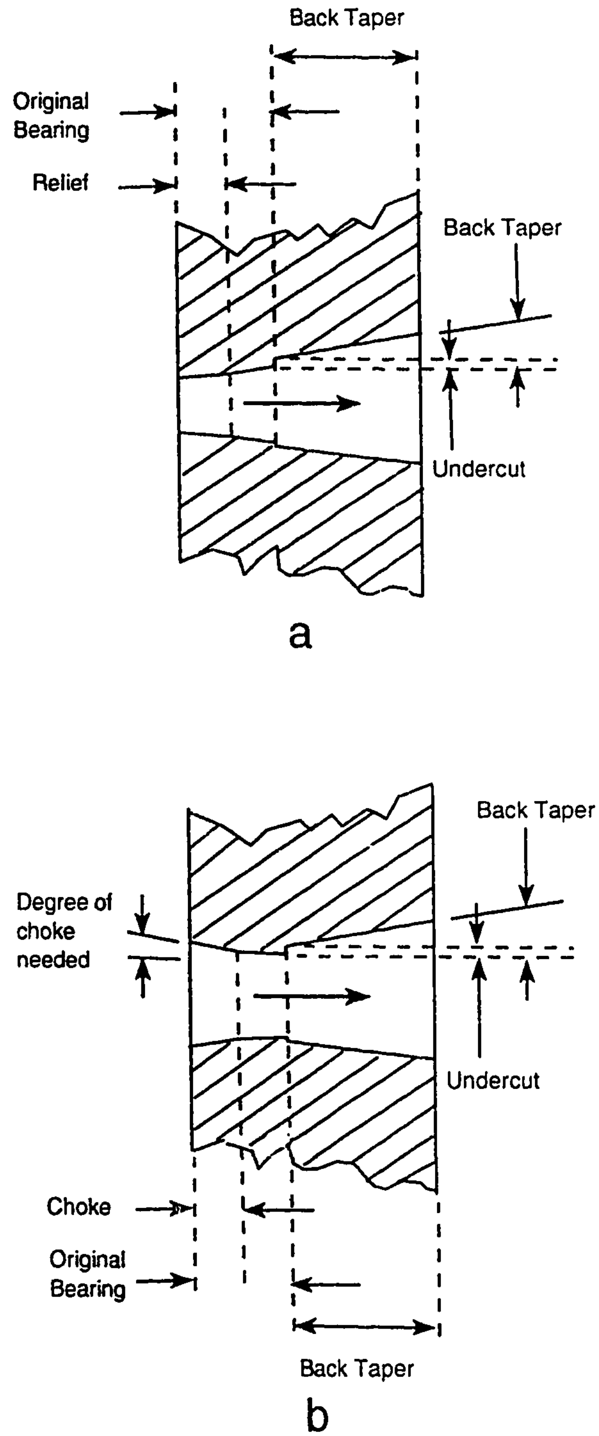


Figure 1.6: Diagram showing (a)relief and (b)choke to control metal flow through a die.

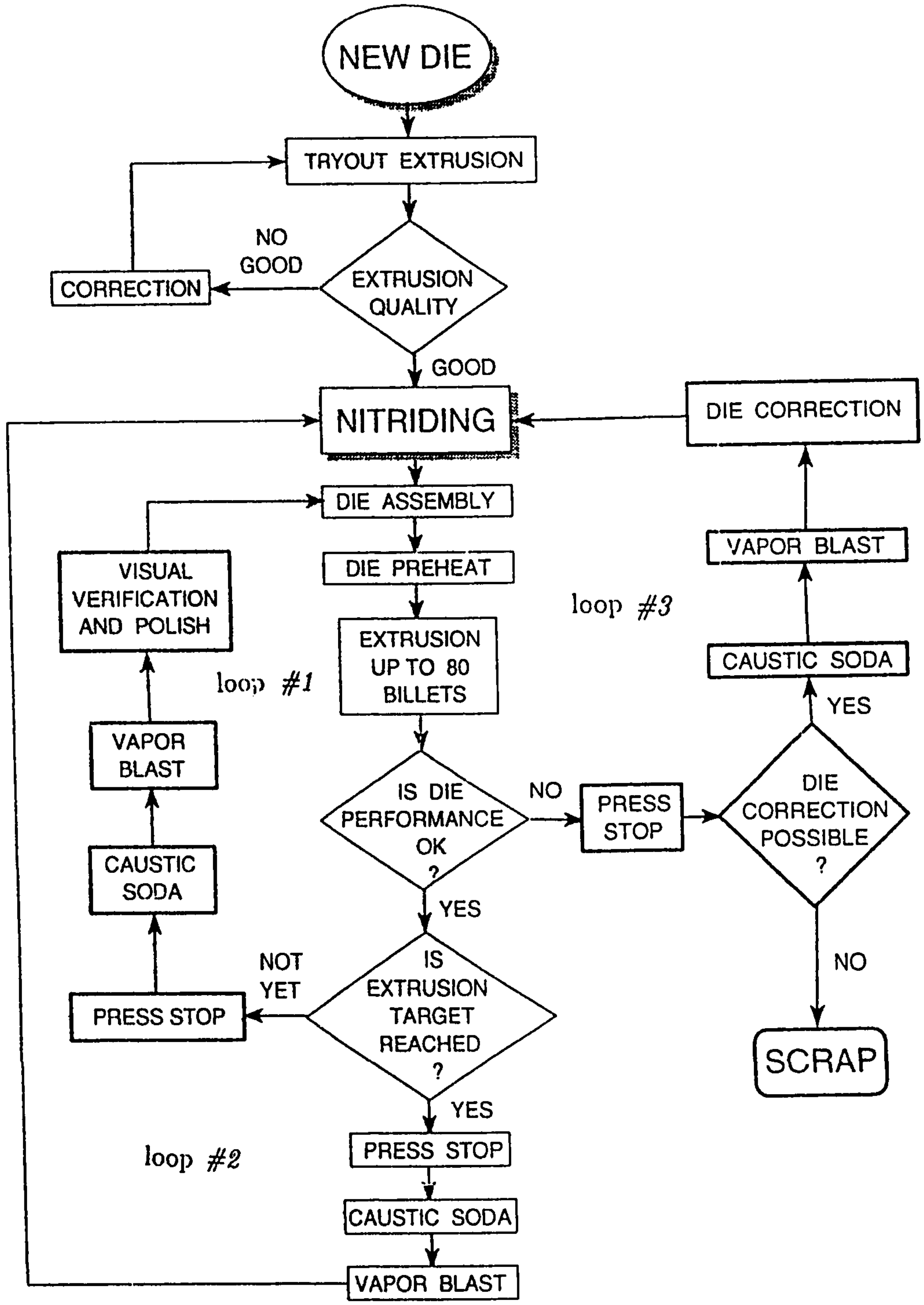


Figure 1.7: Schematic representation of the die circulation flow chart using the extrusion target weight concept.

- After the new die is tried and accepted, it is sent for nitriding and then it is directly mounted on the press without any corrections or polishing.

- At first, in the press with a cooling system, an average of up to 80 billets through solid dies or 50 billets through hollow dies are pushed in a single run. This sequence is denoted by the small loop *#1* shown in Fig. 1.6. After completion of the run, the die is cleaned, dimensions and bearing surface are inspected and verified visually and put back into production after quick polish.

- Eighty billets, however, are usually not enough to fill an order or reach the extrusion target weight (order placed by the consumer). Therefore, the *#1* loop is repeated several times until the recommended extrusion weight is reached. If there is a residual life available in the die after fulfilling the required order then, the die is taken out of production, cleaned, verified (dimensions checked) and sent for nitriding. This operation is denoted by the large loop *#2* in the chart. During the entire die life the *#1* and *#2* loop are repeated many times. The *#2* loop is run usually 10 to 15 times before a die is scrapped. For a large order or target weight, a number of dies may go through this process.

- Whenever there is a need for an unscheduled die correction, the die enters a loop *#3* in addition to the *#1* and *#2*. This may be caused by either a catastrophic failure(correction may not be possible) or premature chipping or excessive wear at some location(premature die damage and correction is possible). As evident from the industrial data presented in this work, premature die damage is very frequent die maintenance problem facing the extrusion industry. This has provided additional motivation to evaluate the reliability of the die under complex industrial environment.

After discovery of the damage, depending on the severity of the correction required, the corrected die is either sent back to the production or, if the correction was carried out on the bearing surface, it is sent back for nitriding. Failure to re-nitride after interventions on the bearing surface leads to rapid deterioration of the surface and consequently to the deterioration of the extrusion surface quality. When the loop *#3* is followed, the productivity and extrusion efficiency falls down. The frequency with which one has to follow the loop *#3* is closely related to the die reliability. When an in-appropriate nitriding procedures is used, the die reliability is low and *#3* loop is more frequently used. In other words, the die is more often corrected before or during the extrusion process. Following the proper and recommended nitriding procedures results in a high die reliability, and the die circulation follows mainly the *#1* and *#2* loops.

The performance of a die is normally limited by typical material-related failure mechanisms. In the case of aluminum extrusion the most common die failures are due to:

- Cracking/fracture.

- Hot wear/chipping.
- Plastic deformation.

1.3 Die Influence on Product Quality

Along with many other factors that contribute to the surface quality of extruded aluminum, such as, billet quality, extrusion speed, shape integrity, and handling etc, the extrusion die plays a very significant role. Bearing surface is one of the factors which influence the quality. The importance of the extrusion surface is self evident from the care taken in polishing it before it is put into production. The higher the polish on the die the better will be the surface quality of the extruded product. Over the past few years, many die makers have changed over to making dies with Wire EDM and polishing them by extrude honing to manufacture a die with a high quality finish. Before the use of Wire EDM to machine the die opening, graphite electrodes were used in conventional EDM machines. This method of spark erosion would usually leave a porous bearing surface, which requires more hand polishing. The most important thing to remember when polishing a die with the extrude hone is that it will only polish the surface that is already there, and it does not remove any wash out from extruding. The advantage of Wire EDM over conventional EDM is the finer surface finish achieved before the polishing process is initiated.

Another contributing factor to poor surface quality on extrusions can be the transitions between different bearing lengths in the die. A transition between bearing lengths must be smooth and gradual without any sharp corners. The bearing changes are usually found where there is a heavy section of the extrusion with a thinner leg or area next to it. A drastic change in the section sizes requires a drastic bearing transition to control the flow of aluminum. Die lines usually show up in the areas where these drastic bearing changes take place, especially where the bearings are dropped sharply and not rolled and positioned properly. When the bearing change is not positioned properly, it results in poor surface finish and appearance of irregular surface on the extruded profile. As evident from the above mentioned discussion, the extrusion die plays an important role in the quality of the extruded aluminum products.

When a die is used in production, notes are taken by observing the extruded profile quality. Then, when these dies are returned to the die shop, corrective measures are taken. If the profiles are good, smooth, dimensions within the tolerance limits, weight per meter in the acceptable range, then nothing is done to the die except some polishing and cleaning or hardening, if needed. On the other hand if the die has any unacceptable roughness, weariness, bad angularity and heavy weight per meter, then corrections must be done, and it becomes obligatory to re-harden the die. Thus, the quality of the product is a major manifestation of the state of the die; and die replacement strategies can be formulated using these manifestations of the product quality.

1.4 Extrusion Die Life Modelling

Advances in modern technology in manufacturing sciences have led to an ever increasing use of computers in controlling the manufacturing operations. For an adequate control of an automated extrusion process, it is essential to have dies of greater reliability, since reliability characterizes the probability of survival of the tools up to a specific life when operating under specified environment.

In an aluminum extrusion process the die is a very critical component and so are the die material and its specific properties which are inherently probabilistic in nature. This, in turn is responsible for the variation of life of an individual extrusion die used in the industry. The statistical distribution of the life thus leads to the concept of the reliability of the die. The reliable prediction of the tool life is important for an economical production because of the associated loss due to an untimely failure of the die, particularly in an automated system when the cost of machine stoppage is quite high due to productivity losses and poor quality product. In addition, the expenses involved in untimely change of the tool are much higher and an unscheduled replacement may contribute to a significant part of the total expenditure involved in production. Tooling costs form a significant portion of finished product cost in any industrial hot-working process. In the forging industry for example, it has been stated that die cost represents (on an average) 10% of the unit cost of a forged component. Additionally, process costs are indirectly affected by the machine downtime involved in die repair or replacement. While premature failure can be avoided by correct design practice and careful control of the process conditions and maintenance, a tool or die still has to be discarded or corrected in service when wear exceeds acceptable tolerance limits. The economics of an extruded semi-finished product are not least governed by the tooling cost and therefore the die life. The service life of a die is normally limited. It depends on the die itself i.e. the die material, the heat treatment and the material properties, and on the design and manufacture of it. The working conditions also play a crucial role e.g. the alloy being extruded, the extrusion temperature, the deformation resistance, extrusion time, extrusion speed and many other factors.

The fact that the tool life in general is typically stochastic in nature and hence governed by the laws of probability has been well appreciated in literature [5]. In literature mostly the cutting tools have been studied in a probabilistic frame work. There is a lack of probabilistic treatment for tools used in metal forming, in particular for extrusion dies. In this work tool life modelling concepts used in machining systems are extended to the forming process specifically, extrusion, in order to predict the die life. The life of extrusion die is limited due to cyclic loading, and abrasion i.e., fatigue, and wear are considered to be the dominating modes of failure.

The knowledge of the die life is useful not only in predicting the number of dies required to suffice a production order but also to compare the different dies on the basis of their quality, complexity, nature of heat treatment performed, reconditioning or manufacturing in the plant or for comparison of the quality of the dies supplied by the different suppliers and, this information can as well be used in designing a die to with stand a defined number of stress cycles.

Sheikh et al. [6, 7] have demonstrated that Weibull reliability model is an appropriate model to be used in the reliable life prediction of cutting tools, because of a number of reasons. some of which are mentioned below.

i) Monotonically increasing failure rate of the tools is best characterized by the Weibull failure rate model.

ii) It is the life model obtained as an outcome of extreme value phenomenon of tool damage which is quite relevant to the tool failure phenomenon (i.e. extreme damage due to crack propagation or/and wear reaching a critical level).

iii) The Weibull model comparatively is the most conservative model.

iv) The versatility of the model. its flexibility and the ability to be expressed in a closed form to accommodate a number of shapes of distributions by varying its parameters.

v) Adequate computerized means of estimating the Weibull model's parameters are available. The statistical estimates can be easily obtained with relatively little data. This becomes extremely important in case of expensive testing procedures, or when one has to rely on actual field test data.

Therefore weibull model will be hypothasised to characterize the extrusion die life obtained from industry. Primarily the reliability of an extrusion die will be evaluated through the real life industrial data acquired from ALUPCO (Aluminum Product Company at Dammam). Using the failure history of different types of solid, hollow, simple and complex extruded section dies, it will be shown that both 2 and 3 parameter weibull reliability model best represent the data adequately. The Weibull distribution will be fitted to all the available die life data and its validity will be checked by fitting a straight line by regression to a suitably transformed tool life data. Further the shape and scale parameters of the Weibull model will be estimated. This will provide an invaluable information useful in the reliability analysis for predictive and planning purposes.

It is important to emphasize that the real life data such as that obtained from the industry is very valuable, since the cost of setting up such prototype identical laboratory test facility would cost millions of Riyals.

The effect of the complexity of the shape on the life of the die(die complexity) will be determined by establishing its correlation with shape and scale parameters of the model. It will be shown that complexity definitions already available in the literature are in general inadequate, being unable to incorporate important parameters like extrusion ratio, number of die cavities, tongue ratio, etc. Hence new complexity definitions verified through an extensive pool of data will be proposed. Based on these complexity factors the life of different dies will be estimated and compared with the actual industrial data. A good agreement observed will demonstrate the appropriateness of the new die complexity definition for predicting the reliable die life.

The task of predicting the die life analytically, using an appropriate die damage model is a difficult problem, however the non-availability of the reliable die life data and the amount of expenses that are involved in providing such data experimentally, make the mathematical die life model an important means of determining the die life distribution by simulation. On the basis of well established fatigue, fracture and wear theories the *Monte Carlo Simulation* will be conducted in predicting the die life. The main aspect of Monte Carlo Simulation is that the inherent variability of the different contributing variables can be used to synthesize on the distribution of the life of the dies. without actual waiting for their time to failure. This is a promising approach as will be illustrated by comparison of the predicted and actual (industrial) life of dies. For the simulated set of die life data, the reliability $R(t)$, cumulative distribution function(CDF) $F(t)$, probability density function(PDF) $f(t)$ and the failure rate $\lambda(t)$ are established along with the model and data curves; the model being generated from the parameters which were initially extracted by the statistical analysis of individual dies and the data curves obtained by plotting the raw data grouped or ungrouped directly on the graph. The die life data will be plotted on the Weibull probability paper (i.e., transformed data is plotted on a linear paper) and the validity of the Weibull distribution as a suitable model will be established.

Finally, recommendations for enhancement of the die life will be proposed, and major areas in die maintenance strategies such as die correction, alignment and rehardening which have a significant role on the final product quality are addressed, with an ultimate objective to set an appropriate interval for inspection, repair and maintenance.

1.5 The Scope of the Work

In summary the following specific tasks will be undertaken during this work:

Task 1) Literature Review.

Literature survey will be done. which will consist of two parts: tool reliability literature survey to emulate the similar pattern of statistical thinking to model life of extrusion dies, and the review of extrusion die surface hardening techniques.

Task 2) Die Failure Mechanism and Modes of failure.

Typical extrusion die failure causes and mechanisms will be reviewed, and the major modes of die failure will be explored.

Task 3) Statistical Analysis of Die Life Data.

A comprehensive statistical analysis of the historical die life data coming from the plant will be done to find out the appropriate reliability model describing the die life in industry. In addition to it, the reliable life of an extrusion die will be predicted through the various definitions of complexity of the profile being extruded through it. Complexity definitions in literature will be evaluated, and more appropriate new complexity definitions will be proposed.

Task 4) Predicting the Die Life by Fracture Mechanics and wear based Models.

A fracture mechanics fatigue life prediction model will be developed to find out the life of die which failed due to fracture alone. To simulate the life of dies failed due to wear. another model based on the wear theory will be proposed, and simulations will be conducted. Finally, a comprehensive competitive risk model will be proposed to account for all the causes together.

Task 5) Enhancement of Die Life by Surface Hardening.

With the rational that life of an extrusion die is a trade off between hardness and toughness. die enhancement strategies will be proposed for improving heat treatment methodology to select an optimal hardness, which will provide a best combination of both hardness and toughness.

Task 6) Conclusions.

Finally, the conclusions will be drawn from the results and recommendations for future work will be presented.

Chapter 2

Literature Review

In any production process, the unpredictable and unscheduled nature of the die (or tool) failure leads to the requirement of greater man power and delays in meeting the production targets. this adds additional expenses to the total manufacturing cost. Uncertain failure of a die in an extrusion press necessitates the stoppage of the extrusion system and as a consequence the productivity is lost causing an economical loss to the company. The overall reliability of an extrusion plant is significantly affected by the reliability of the tool or the die being used. Though wear of the tools in general is an important failure phenomenon, it may not lead to an unexpected failure. The crack propagation due to the cyclic nature of loading and an ultimate fatigue is considered to be the predominant mechanism leading to die fracture. In order to maintain an optimal production, control must be precise with respect to when the dies are to be removed from use, particularly in an automated manufacturing system. This has molded down to the concept of life prediction of an extrusion die, to make the system more reliable and to adopt a better die replacement policy which would reduce the risk of an unscheduled failure and thus reduce the extra costs involved with the untimely failure.

The probabilistic approach applied to evaluate the life of an extrusion die is quite new approach, and there was not much literature available pertaining to the issue. In literature similar statistical approaches have been successfully used in cutting tools which are used in machining operations. Therefore Lee et al. [8] and Levi et al. [9] and others which dealt with the general tool fracture probability in machining situation were consulted to emulate the similar thinking patterns and ideas in the current research.

Barsh and Wagner [5] first showed that tool life values follow a statistical distribution, on the basis of hundreds of experiments conducted using high speed steel tools. Kendall and Sheikh [10, 6, 7] presented various tool reliability models and pointed out that an important index of tool reliability is the coefficient of variation of tool life. The various tool replacement strategies and optimum cutting rates based on a tool reliability model are also discussed. Later, the benefits of using probabilistic models for tool replacement decisions are presented. In another paper Sheikh [11] discussed some deterministic and probabilistic approaches for tool life modelling, and proposed some theoretical and empirical foundations of the Log-Normal and Weibull tool reliability models based on statistical analysis of tool failure data.

Just like the tool life the life of an extrusion die is not a deterministic value, it ranges from a few billets extruded to a hundreds of billets being extruded before the failure, the reason being the stochastic nature of the variables involved. The effect of the inherent statistical variability of the different variables of any proposed die life prediction model such as initial crack length, fracture toughness and flow stress etc. on the distribution of the die life can be very well approximated by applying the Monte Carlo technique [12].

W. Reiss [13] in his work showed that tool life in bulk metal forming is limited both by wear and fracture. Due to the variation in life of the individual tools, the reliability of the operation is low. He showed that for reducing tool cost a reduction of the absolute cost of tools as well as an increase of tool life should be achieved. Tool failure should either be avoided or it should be made predictable for reducing costs by interrupted production. In this work tool fracture in solid forward extrusion has been investigated. For this purpose mechanical properties of the specimen of the tool steel were related to the tool life in extrusion tests under simulated production conditions. The results of the investigation enabled an estimation of tool life.

The effect of the extrusion ratio (billet area divided by profile area) on the die life is discussed in reference [14]. With a relatively low extrusion ratio of about 10 to 1, die life is short but mandrel life is relatively long. However, even with simple shape such as a tube, die life and mandrel life are short at high extrusion ratios. Similarly, it is shown through data analysis that die life also varies with the change in complexity of the extruded profile. It is shown for type 410 stainless steel at an intermediate extrusion ratio of 18.5 to 1 that die life for a given die steel and hardness is much shorter if the extrusion being done are irregular or complex shape. The author concluded that die life is further reduced if, as in common, the hardness of the die must be reduced by about five points HRC to reduce the probability of breakage.

The wear resistance of a tool steel is a function of temperature. at high temperature such as that experienced in extrusion, the die is most vulnerable to wear. This fact is well supported by Tittagala et al. [15].

2.1 Surface Hardening

Within the manufacturing process and operation of an aluminum extrusion die, the type of heat treatment, and in particular the surface treatment of the die, has long been a particularly sensitive subject among engineers and metallurgists. Generally, surface treatments fall in two categories: an external coating may be applied to the die, or the die surface may be modified by a diffusion process in order to form an intrinsic surface layer. The latter type, that include nitriding and carbo-nitriding is widely applied in extrusion industry and while they do not necessarily enhance the surface quality of the extrudate, they significantly increase useful die life. Nitriding has been found to be the most suitable method of enhancing the surface characteristics of the die against erosion by aluminum oxide from the extrusion billet. Applied coatings, such as transition metal nitrides applied by chemical or physical vapor deposition (CVD or PVD) are not tried and tested on extrusion tooling, but their introduction may have benefits in terms of surface quality due to their lower affinity for aluminum. as well as offering extended die life. These types of coatings have found favour for cutting tools and in applications where enhanced wear resistance is required.

Gonzales [16] considers several methods of hardening extrusion dies for a large extrusion company and the fluidized bed method is chosen to be the best, capable of both nitrocarburizing and nitriding. Both methods have been applied and compared with unhardened dies of identical design. Research suggest that nitrocarburizing increases die life significantly (by 143% in a representative case) with more stable product dimensions. and nitriding may increase die life still more. The author through examples proves that nitriding is the best process for general use.

There are many surface treatments available for aluminum extrusion dies whose application offers potential increase in die life and running speed, as well as improvement in product quality. In the work by Mew et al. [17], a selection of these treatments is compared, covering those coatings commercially available and commonly used as well as novel treatments not normally applied to extrusion tooling. The tests used in this evaluation were selected and developed to take account of the particular condition under which extrusion dies are used. Mew et al. [17] found from experimental investigations that the coating of chromium nitride onto a pre-nitrided substrate gave the best overall performance in terms of coating adhesion, resistance to damage by scratching and diminished adhesion of aluminum to the die land and resistance to spalling during *CONFORM* extrusion. Visually, the product extruded with this die had a better surface finish. This suggest that use of this coating of chromium nitride onto a nitrided substrate could yield benefits in terms of product quality and improved running speed when applied to extrusion die.

David's [18] work is intended as a review of the existing surface heat treatment methods, and a comparison of these methods against *Plasma Nitriding* technology. As nitrogen and hydrogen for plasma nitriding are supplied from independent, separate, storage tanks, any nitrogen/hydrogen ratio can be selected to meet the requirements, which is very difficult to control in conventional nitriding techniques. The research further mentions that pulsed plasma nitriders permit accurate control over compound zone chemistry because the,

- Process gas mixture can be accurately controlled over a wide range of partial pressures.
- Total gas pressure can be separately controlled.
- Concentration of nitrogen ions and, therefore, the nitrogen activity can separately be controlled.

The author further claims that pulse plasma nitriding gives better metallurgical control compared with the conventional process. The case formation can be either single phase or dual phase. When a component is sensitive to thermal exposure, either for core properties or distortion risk, then lower operating temperatures can be selected.

The endurance limit of hot-worked die steels at working temperatures has been found by Wallbank et al. [19] to correlate with die life when fracture is the controlling failure mechanism. Also metallurgical examination performed by the author shows that the endurance limit is related to the microstructural features. The paper further points out that the use of electric-discharge machining (EDM) has a significant effect on the endurance limit. A mechanism of oxidation aided wear has been considered for dies which wear out-of-tolerance. The possible wear of the EDM surface by plucking has been examined. The fatigue properties of die steels were tested with two main objectives. The first was to establish a relationship between fatigue properties and die life as experienced on the shop floor. This would then enable the fatigue test to be used to assess the effect of various factors on die life. The second reason was to discover what affect various electric-discharge machining (EDM) finishes would have on the fatigue properties and hence the die life.

The implications of the extrusion dies condition on the surface quality of the product are well discussed in [20]. The author establishes the importance of the bearing surface and bearing length transitions on the surface integrity of the extruded profile. The cause of the formation of die lines is also discussed in detail. The reliability and maintainability is very crucial for the better surface of the extruded product. Clode et al. [21] discussed the die lines phenomenon during extruding AA-6063 and also established the effect of temperature and strain rate. The influence of die land length on the surface generated features is also determined. The results indicate that the surface formation mechanism is one of generation and modification; the surface is generated on the leading edge of the die land in the absence of oxygen and interacts thereafter with the remainder of the die land, resulting in material transfer between extrudate and die land, thus increasing the surface roughness and consequently reducing the die life. Experiments conducted utilizing alloy AA-2014, AA-5456 and AA-7075 indicated two causes of the defects known as "cracks and tears", one being incipient melting, the other due to differential changes in structure during deformation.

The aluminum extruders council has a three part training program for the correction of solid extrusion dies. References [22, 23] describe procedures for handling and maintenance of extrusion dies and tools.

2.2 New Tool Material

A quite new type of precipitation hardening die steel with a properties-profile particularly optimized for aluminum extrusion dies has recently been developed. This new steel [24] can offer easier and more rapid die making than AISI H-13, and at the same time significantly increases in die life can be achieved. $ALEX^R$ is a new type of low alloyed maraging steel strengthened by precipitation hardening (PH). It is low carbon type steel, mainly based on manganese, chromium, nickel and aluminum as alloying elements. The author claims that the hot wear resistance of nitrided $ALEX^R$ is better than in nitrided AISI H-13, which means that $ALEX^R$ can improve die life in cases where wear is the main reason for die failure.

Chapter 3

Extrusion Dies Operating Environment, Modes of Die Failures and Contributing Factors

3.1 Extrusion Dies Operating Environment

A number of causes are considered to be responsible for initiating the damage of an extrusion die before its designated life is reached. An extrusion die is exposed to high temperatures derived not only from the heated billet but also from heat generated by deformation and friction. In addition, the die is subjected to high pressure and, in the area of the die land, considerable frictional forces. The extrusion dies work in the temperature range of 400 *to* 470°C, while the stress or pressure is in the range of 2000 *to* 2700psi. The stresses experienced by an extrusion die in service are both mechanical and thermal in origin. However, the thermal stresses arising from temperature differences are generally quite moderate in extrusion where the temperature changes occur only fairly slowly. Hence, thermal fatigue cracks develop more gradually in extrusion than in other processes where hot-worked steels are used and where the temperature cycles are much more severe e.g. die casting. On the other hand, wear and fracture are very pronounced in extrusion.

The nature of stress is cyclic, with the maximum reaching upto 2700psi and a minimum of zero. This can be seen in Fig. 1.2, which elaborates a extrusion pressure cycle. Action of cyclic stress in presence of initial cracks (which are often generated during machining and heat treatment), can lead to crack growth and ultimate fatigue failure.

In aluminum extrusion, the hard oxide film (Al_2O_3), which forms instantaneously on the surface of the extruded metal, causes extensive abrasion of the die during service. Due to the rubbing action, the die wears out of tolerance rendering inaccurate dimensions of the extruded product. This wear is not equal at all places but it is more pronounced at places of high stress concentration i.e. at intricate details, corners, etc.

The imbalance of forces, caused in the case of non-symmetric profiles causes the die mandrel to deform plastically. This deflection of the die mandrel causes two fold problems, one is that it causes additional stress on the die surface causing early breakage, the other is that it can in severe cases cause mandrel fracture.

Die life is therefore finite and is limited by (in order of importance);

- Formation of inherent micro quench cracks during heat treatment, and their propagation with respect to time.
- Wear.
- Plastic deformation(web deflection) or cracking and indentation, caused due to instability of support tooling.

The third factor mentioned above deserves comment. Plastic deformation or even cracking of dies can occur particularly when extruding very complicated profiles through dies with high tongue ratios. In this case, the very great stress on the tongue combined with the locally high temperature can cause bending; in some instances, the tongue can actually break off if the transverse toughness of the steel is inadequate. A tool steel with good hot strength and sufficient transverse toughness is a must for dies with high tongue ratios. Fig. 3.1 shows a typical solid section die used in Aluminum extrusion.

3.2 Failure Analysis and Modes of Die Failure

Analysis of tool and die failure is substantially aided by the knowledge of the manufacturing and service history of the failed tool or die. In many instances, however,

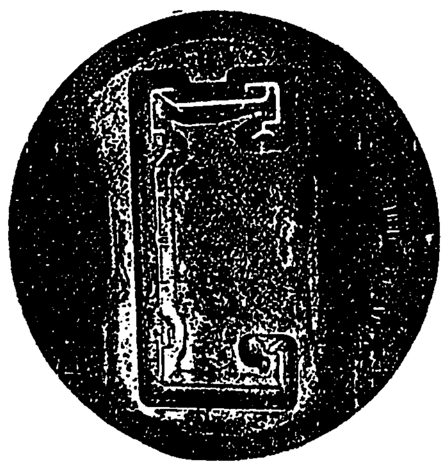


Figure 3.1: Typical Extrusion Die.

such information is sketchy, and the analyst must rely on experience and engineering judgement. Before beginning the investigation, a complete history of the manufacture and service life should be compiled. Next, the die must be carefully examined, measured and photographed to document the extent and location of the damage. The origin of the damage, when due to fracture, will also usually be determined. The composition of the die should be verified by reliable methods. Tool and die failures occasionally result from accidental use of the wrong grade of steel. Macroscopic examination of the fracture features can be done by opening tight cracks (when present). Because quench cracking is very common cause of failures, the fracture surfaces should always be checked for temper color. Scale on a crack wall would indicate that it was exposed to temperature higher than those used in tempering [25].

Visual inspection of the damage done to a tool and die is usually adequate to classify the type of tool and die failure. High-magnification fractographic examination is required in only a small percentage of the cases. Microstructural examination at and away from the damage and at the origin is imperative. This generally requires good edge-retention preparation, which is relatively easy for tool steels. A large percentage of tool and die failures is due to heat treatment problems, the importance of proper metallographic procedures cannot be stressed enough. Premature damage of tools are described and advice given on how to avoid such failures. The goal of any failure analyst should be to provide a total picture of all the problems present so that a complete corrective action, rather than a partial corrective action, is taken in future. Aside from cracking, a wide variety of problems can be encountered that cause limited tool or die life. These problems include, but are not limited to, distortion (during heat treatment, machining, or service), excessive wear galling, pick-up, erosion, pitting, cosmetic problems, and corrosion problems. In literature a number of articles report the result of such failure analysis performed on the failed dies as shown in Fig. 3.2 [26] and the most commonly observed modes of die failure are:

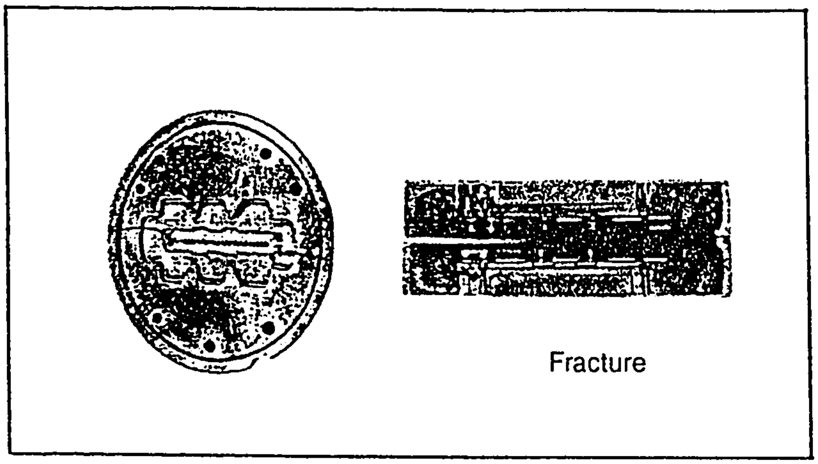
i) Crack propagation.

ii) Wear, and

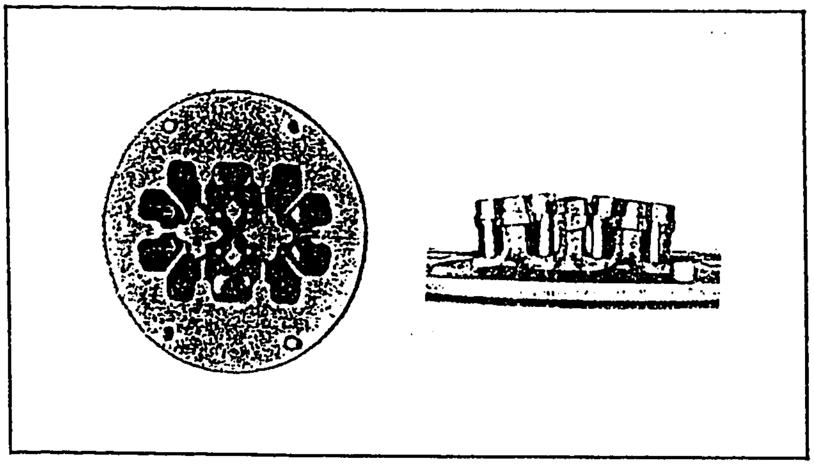
iii) Deflection.

3.2.1 Fatigue due to Crack Growth

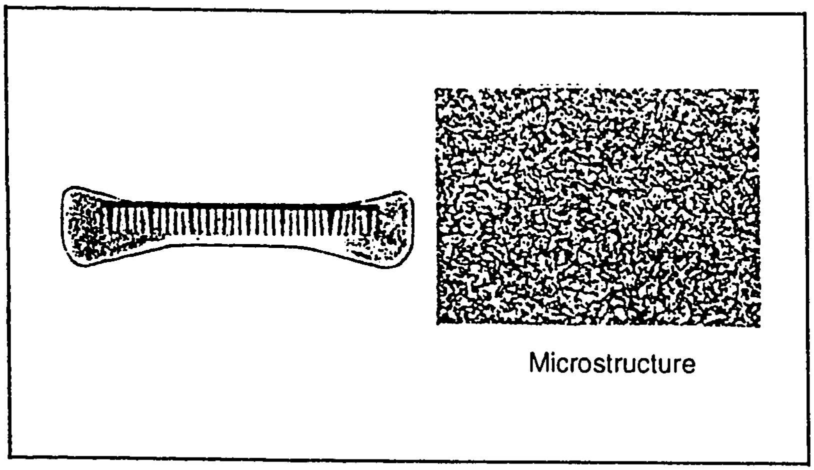
Most tools and dies fail in brittle manner, fatigue failure is considered to be the primary cause. In most cases, the fatigue failure is located at a change in section size, at a sharp corner, or at stamp marks. Various aspects of the operating nature of these dies suggest a potential for failure resulting from the growth of cracks on the bearing surface. First, during normal operations, the dies are subjected to large, cyclic stresses. Second, the cavities in both dies create regions of high stress concentration specially at race ways and at intricate braces, where cracks



Cracked extrusion die. Cause: insufficent preheating and heat treatment failure



Plastic deformation on an extrusion die (H-13) due to heat treatment failure



Extrusion die (H-11) failed due to underhardening

Figure 3.2: Figure showing typical failures of aluminum extrusion dies.

can initiate and grow resulting in catastrophic failure. Third, in order to produce profiles of well controlled shape and dimensions, the dies are made of high strength, hardened material for e.g.(H-13). As such they must be prone to brittle fatigue fracture.

Die material and heat treatment should produce minimum initial cracks and provide greatest fracture toughness to resist die breakage under fatigue crack growth.

3.2.2 Wear Failures

Wear also constitutes a sizable cause of die failure. During the pre-heating of the aluminum billet, aluminum oxide(Al_2O_3) is formed on the surface. This oxide of aluminum is very hard, it's hardness is comparable to the hardness of some compounds of diamond. Also, when the die is heated prior to extrusion, a film of iron oxide is formed on the die bearing surface. The combined effect of these two phenomena results in the wear of the bearing surface. It is observed that the wear is more pronounced at locations of high stress concentration, resulting in wearing the die cavity unevenly.

Die material should have a wear resistant surface, hence a proper surface treatment is essential to create such a surface, and tool material should be adaptable to this treatment without a greater sacrifice of toughness.

3.2.3 Deflection of Mandrel and other Plastic Deformation Related Failures

One of the main causes that promote the extrusion die failure is the die deflection which causes a part of the die surface to get deflected due to high extrusion pressures acting at the center of opening and decreasing radially outwards. This is observed particularly when the die opening is wide making the die weak at the corners of the opening with higher stress intensity at that point. The movement of the die surface along the corners of the opening is considered to be responsible for the die deflection.

Some dies also fail due to the mandrel deflection or due to the plastic deformation. The primary reason for this type of failure is the unbalanced stress acting on the die face, either due to misalignment or due to poor die design. This type of failure is often observed in dies which extrude un-symmetric profiles. The extent of the deflection can be discovered by observing cracks on the mandrel.

Die and mandrel material should be such that it has high strength, at high temperature and the geometry should be such which provide high stiffness. Some other desirable aspects of extrusion dies to minimize the failures are [25]:

- Mechanical Design must be compatible with the steel grade selected, the procedures required to manufacture the tool or die, and the use of the tool or die.

- Grade Selection must be compatible with the design chosen, the manufacturing process used to produce the tool or die, and the intended service conditions and desired life.

- Steel Quality must be microstructurally sound, free of harmful inclusions to the degree required for the application, and free of harmful surface defects.

- Machining Process must not alter the surface microstructure or surface finish and must not produce excessive residual stresses that will promote heat-treatment problems or service failures.

- Heat treatment operations must produce the desired microstructure, hardness, toughness and hardenability at the surface and the interior.

- Grinding and finishing operations must not impair the surface integrity of the component.

- Tool and die set up alignment must be precise to avoid irregular, excessive stresses that will accelerate wear or cause cracking.

- Tool and die operation overloading must be avoided to ensure achievement of the desired component life.

3.3 Typical Die Materials to Resist above Modes of Failures

Materials used for hot extrusion tooling vary with the actual application. High quality materials, however, are essential for all applications. Desirable properties for tooling materials to withstand the high mechanical and thermal stresses encountered include:

1. High toughness and resistance to softening/hot hardness.
2. High resistance to abrasive wear at elevated temperature.
3. Adequate strength at high temperature.
4. Resistance to distortion and cracking from tensile stresses developed during heat treatment, as well as from temperature changes during extruding, which can initiate hot cracking.
5. Acceptable resistance to thermal fatigue cracking.
6. High thermal conductivity to continuously remove heat from the area of contact with the hot billet.

Resistance to softening is an important requirement for tooling materials operating at high temperatures. When tool and alloy steel are used, this resistance is controlled primarily by the addition of tungsten, molybdenum, and vanadium alloying elements. Selection of the optimum grade for a given application is generally a compromise between toughness and wear resistance, although other factors may be more important in certain situations. Because most tools and dies operate under highly stressed conditions, toughness must be adequate to prevent brittle fracture. It is usually better for a tool or die to wear out than to break in service prematurely. Thus, in a new application, it is best to select a grade that will definitely have adequate toughness. A typical aluminum extrusion die is made of H-12 or H-13 (classified by AISI), but in ALUPCO primarily H-13 (high chrome) dies are used. with hardness 48-60 RC (nitrided) with a typical fracture toughness of 80 $MPa\sqrt{m}$ at room temperature. H-13 steels is perceived to provide good blend of desirable properties (characteristics) against the three modes of die failure, and to render a good die life.

3.4 Relative Contribution of Various Modes of Die Failure in an Aluminum Extrusion Plant

Analysing around 1400 die failure histories obtained from ALUPCO, the dies were categorized according to the causes of failure and the results are shown in Table 3.1. which clearly reveals the mode of die failure for each die set(Die No.). Figure 3.3 shows a pie chart, drawn to elaborate the proportion of each mode of failure, three major reasons(modes) of die failures are; fatigue, deflection and plastic deformation and wear. In the analysed data, around 40% of all die failure was found to be caused by crack propagation which resulted in die failure attributed to fatigue, the other cause of failure was wear or over weight(27%), while mandrel deflection is another significant cause of die scrapage(35%). Mandrel deflection sometimes can be attributed to excessive wear

3.5 Factors Contributing to Die Failure

Die failures can be attributed to the following causes:

- Incorrect material selection and steel defects
- Die design and complexity of the product related factors
- Incorrect tool manufacturing
- Incorrect heat treatment
- Incorrect use in service
- Enhancement of failure rates due to intensification of operating conditions

Table 3.1: Table showing the modes of failure of aluminum extrusion dies (Data courtesy of ALUPCO).

S No.	Die No.	Modes of Die Failure			
		Fracture (Nf)	Wear (Nw)	Deflection (Nd)	Total (Nt)
1	H9028	36	39	40	115
2	H4525	23	8	22	53
3	H9049	0	8	0	8
4	H9046	4	12	7	23
5	H9023	1	2	6	9
6	H9050	1	7	1	9
7	S9064	6	0	1	7
8	S9017	12	7	2	21
9	H9022	1	5	3	9
10	H9019	75	42	46	163
11	H1464	6	15	10	31
12	H1577	11	16	11	38
13	H9026	18	37	96	151
14	H1553	1	7	5	13
15	H9062	3	3	7	13
16	H5178	8	3	32	43
17	H9009	37	17	19	73
18	H9057	22	16	34	72
19	H9008	28	24	52	104
20	S9006	83	10	14	107
21	S9070	43	9	1	53
22	H9032	37	42	62	141
23	S1466	2	14	0	16
24	H9052	3	7	3	13
25	S1465	6	16	10	32
26	S9031	35	4	1	40
27	S9030	9	0	0	9
28	S1113	3	5	1	9
29	S9029	14	3	0	17

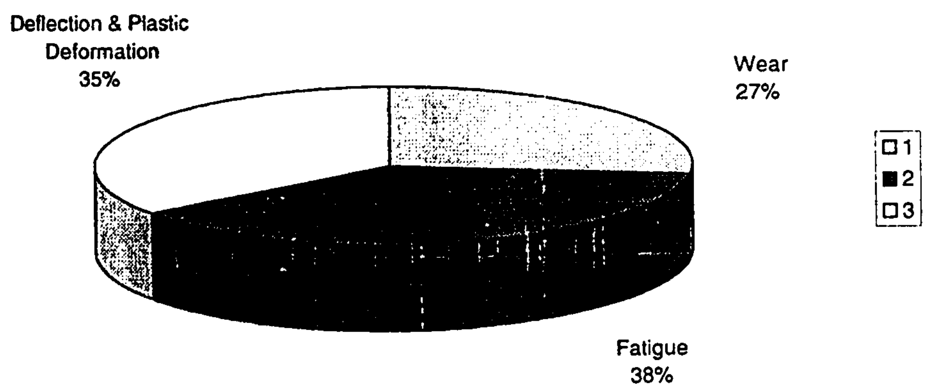


Figure 3.3: Pie chart showing the major causes of extrusion die failure in industry. (Data obtained from ALUPCO)

3.5.1 Materials Related Factors

Shape-forming extrusion dies are subjected to the highest stresses in terms of compression, friction and wear. Since, tool is usually a very expensive labour-intensive component, a high through-put is aimed for. Consequently, a large number of factors must be taken into consideration in the design, material selection, manufacture, heat treatment and working conditions in order to achieve the desired high through put. Steel defects have been seen to cause failure, it was observed that pores appeared in the core during the finish machining of the die. Numerous dies failed prematurely by a combination of material and heat treatment defects. Case histories show that the microstructure of the broken die exhibited severe grain boundary carbide. If, as in this case, there is also an insufficient degree of solubility of carbides during the heat treatment, a perfect heat treatment structure cannot be achieved if the annealed structure of the starting material is imperfect: severe precipitation of grain boundary carbides impairs the ductility and temperature fluctuation resistance. These precipitates are dissolved by an intermediate special heat treatment after hot working.

Large particles of impurities carried by the work material exert a very high pressure when passing through sharp corners of the die opening, thus causing fracture of the sharp die corners.

3.5.2 Complexity of the Product and Die Design Related Factors

The design and manufacture of extrusion dies is a highly specialized procedure requiring skilled die makers. It is necessary at the design stage to make proper allowance for shrinkage, elastic deformation, the nature of the profile section and the highly uneven velocity distribution when extruding complicated profiles (so that the profile remains more or less straight when extruded). The following criteria should be fulfilled during die design and manufacture:

- Very tight tolerances, so that the extruded profile does not have excessive weight per unit length (material yield).
- Correct die geometry from the beginning, thereby avoiding expensive reworking.
- Carefully finished land surface such that the profile surface is acceptable.
- Proper design, choice of die steel, heat treatment etc. giving maximum die life.
- Rational production resulting in low die manufacturing costs.

Some times the die is choked due to the greater amount of material entering through the ports and being unable to pass through the die opening. This causes the building up of pressure at the opening and causes crack initiation which further grows until it reaches a critical value and fails by fatigue.

The extrusion process permits the production of a wide variety of shapes. Certain limitations imposed by die design and other manufacturing considerations are illustrated by the examples in Fig. 3.4 [27].

1. Thin-walled shapes with large circumscribing circle diameter, such as section *(a)* and *(k)* are difficult to straighten and reduce die life also. A slight increase in wall thickness. or stiffening ribs as indicated in section *(k)* by dotted lines, can help remedy this condition.

2. In shapes with several adjacent die tongues such as a, b and c in section *(a)*, an increase of section thickness **t** between the tongues is desirable.

3. In multihole shapes, adequate thickness between holes is necessary. In section *(c)*, for instance, the center web should be increased to *1/8in.*

4. Shapes requiring large overhanging die tongues, as illustrated in section *(a)*,*(b)* and *(i)*, create die problems. The twisting of the aluminum metal flowing past the die tongues, such as tongue b in section *(a)*, may cause die breakage. Section *(i)* shows an unbalanced tongue; *(j)*, the preferred, balance tongue. The entrance to the tongue should be well rounded, as shown in section *(b)* and *(j)*. If possible, the width of the tongue (shown as **w** in sections *(a)* and *(b)*) should be increased.

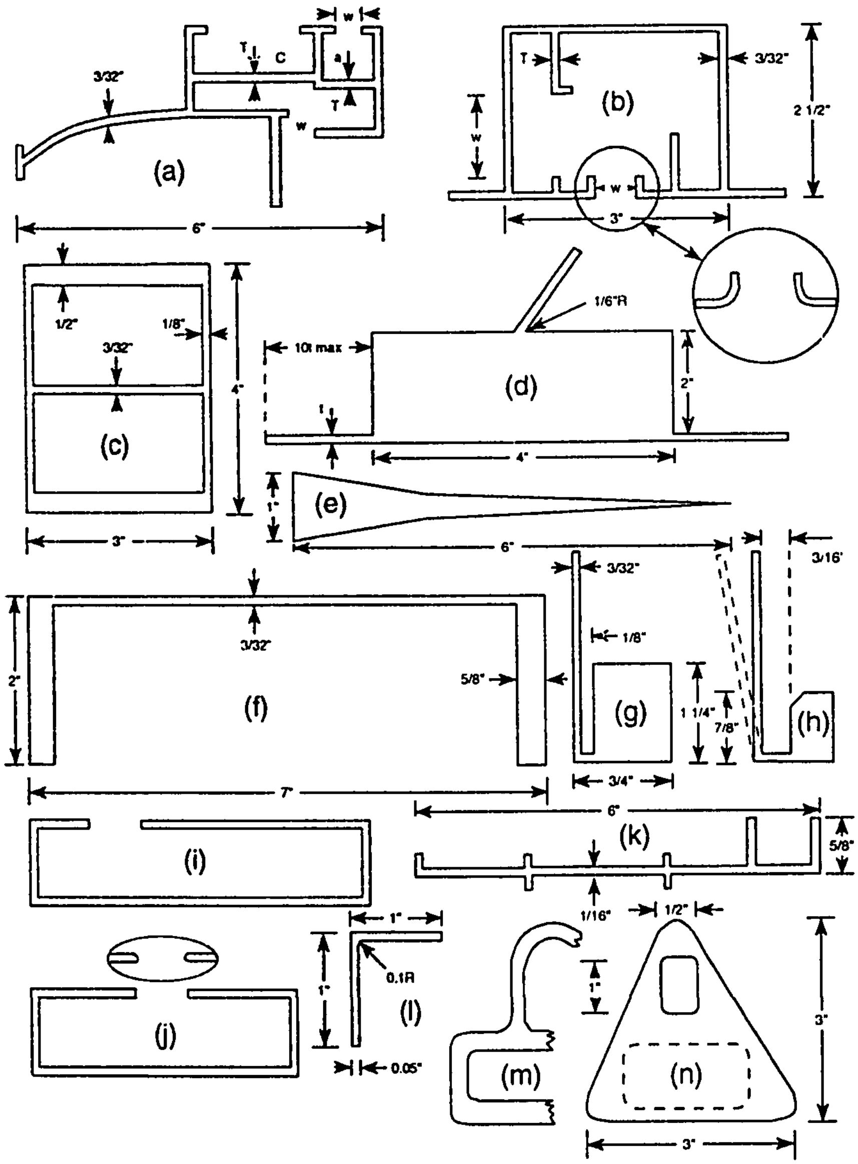


Figure 3.4: Examples of poor extrusion design.

5. Shape *(d)* shows extreme differences of section thickness. To permit control of the metal flow, the length of the thin protruding legs should not exceed 10 times their thickness. Commercial dimensional tolerances are difficult to maintain on these thin legs.

6. In shapes *(e)* and *(f)* which show severe variations from thick to very thin cross-section, straightness and flatness are hard to maintain. Waves tend to form in the thin end of section *(e)*.

7. Shape *(g)*, with a long, narrow tongue flanked by a heavy mass of metal, is undesirable. The preferred design, which should be approached as closely as possible, is shown in *(h)*. Tongue width is increased, tongue depth reduced, the thick section narrowed down, and a radius added at the tongue gap. The radius added defuses the stress concentration at the corner of the die hanging section and thus reduces the failure rate, enhancing the die reliability.

8. In very thin shapes, such as section *(l)*, a general fillet radius helps to maintain straightness tolerances.

3.5.3 Die Manufacturing Related Factors

Die profiles are usually made by spark erosion or wire spark erosion. Care should be taken with both techniques to avoid burning by spark flashover. Despite good rinsing as with wire spark erosion, surface damage cannot be avoided. Eroded peripheral zones exhibit fine cracks, particularly in the so-called white layer, i.e. in the molten zone. There are also severe micro hardness variations because of rehardening and annealing effects. These are associated with high stresses. To reduce the negative effect, erosion should be carried out with sufficient material for polishing.

Grinding

Correct grinding technique will avoid grinding cracks and improve tool life. Tools that have been tempered at low temperatures are especially sensitive during grinding. Only properly dressed, soft, open-grained grinding wheels should be used. The peripheral speed should be restricted and plenty of coolant should be used.

3.5.4 Die Heat Treatment Related Factors

Incorrect heat treatment is the most common cause of premature die damage [26]. Hardness that is too low and inadequately hardened structure considerably reduce the hot strength. Under-hardening also results in premature damage by wear and plastic deformation of the die. Naturally, it is not only the heat treatment but also the steel composition that influences the hot strength of a material. The strength of a material decreases particularly with prolonged loading at high temperatures, even if the annealing temperature is not exceeded. Over-hardening should be avoided just as much as under-hardening. Toughness is reduced considerably by coarsening of the tempered structure and this increases the risk of cracking. In principle, it is possible to carry out rehardening if the heat treatment was incorrect (e.g. if hardness is too low), and, in most practical cases there will be an improvement. Double hardening results in grain coarsening and a reduction in toughness, particularly with large die dimensions.

In every attempt at rehardening, the die must be previously annealed to obtain the favorable initial structure. Care should be taken to carry out this heat treatment in a neutral medium. Carburization must be avoided as much as decarburization of the peripheral zone. The risk of cracking is increased by such a surface defect. Also, the desired hardness is not achieved in decarburized surface zones, resulting in premature wear, particularly in the die opening. The surface quality of the profile is then impaired.

As nitriding provides a deliberate surface change, nitrided surface gives better wear resistance in aluminum extrusion. reduce friction and the tendency to stick and this results in a better surface finish on the section. Over-nitriding must, however be avoided to prevent any negative effect. Severe nitride deposition at the grain boundaries and excessive thick compound zones result in peeling off from the surface. Over-nitriding is caused by nitriding for too long or too frequently. Since the nitrided surface does not wear uniformly in service, an over-nitriding effect can particularly occur at edges after repeated renitriding.

3.5.5 Incorrect Service Related Factors

Tools and dies, even though made from the correct grade, well designed, and properly machined and heat treated, can fail after limited service due to improper operation or mechanical problems. Mechanical factors that may cause premature damages include overloading, overstressing, or alignment/clearance problems. Excessive temperature may be a factor in hot-working die damage, perhaps due to inadequate cooling between operations [28]. Failures have also occurred during assembly for example: during shrink fitting of one part onto another. Stamp marks, in addition to causing heat-treatment failures, can cause service failures due to stress concentration. If a tool fails, it is important to establish the cause and avoid its recurrence.

The improper handling and assembling of a die by the unskilled operators can cause sudden damage of the die. This is common in case of hollow dies when the two parts of the die are not assembled properly and the die is loaded on a press. The sudden application of the extrusion pressure also cause the hard die material to crack and ultimately fail. The inability to maintain a specified temperature of the die during the extrusion process also leads to the failure of the die due to the effect of cyclic nature of thermal loading. Instability of the press due to sudden loading of the billet sets up very high initial extrusion pressures which cause the fatigue failure of the die material particularly at the sharp edges and bends.

Welding

Repair welding is another cause of die damage. It is often the only possible means of saving an expensive tool if the design needs to be modified or broken areas e.g., legs, have to be repaired. This repair should however be carried out with care in order to avoid causing new defects in the repaired region. The transition zone from the welded region to unaffected matrix material is particularly crack sensitive. If examined microscopically the crack are seen running exactly parallel to the white weld zone.

When welding tool steel, special precautions must be taken due to the risk of cracking. Where repair welding is necessary, it is essential to pre-heat the part concerned prior to welding. Immediately after the welding operation:

1. Stress relieve material that has been welded in the soft annealed state.

2. Temper material twice that has been welded in the hardened and tempered condition.

3.5.6 Enhancement of Failure Rates due to Intensification of Operating Conditions

Stem speed

Optimal stem speeds are essential for hot extrusion. Excessive speed can cause over heating of the billet as well as tears and surface defects. A speed that is too slow reduces productivity and increases the required extrusion pressure because of billet cooling. Slow speeds can also decrease tool life because of prolonged contact time between the tools and the hot billet.

Temperature

The operating temperature for aluminum extrusion dictates the efficiency of the process. A temperature which is high, though, gives good die life as the aluminum is very soft, causing reduction in stress and friction, but it does not cold-work the aluminum enough to give it the desired properties. While on the other hand if the working temperature is low, it causes an increase in the working stress and frictional wear, resulting in a decrease of the working life of the die.

Die failure can also occur due to over heating of the die in a furnace before being used on the press. This causes the die material to soften and lose its resistance to withstand high pressure.

Extrusion Ratio

The sections designed must be smaller than the billet diameter used; also, the ratio of the billet area to section area (extrusion ratio) will limit the maximum weight per meter of the shape as well as the length. It must be remembered that the die steel must support the extrusion pressures needed to manufacture a given shape. For this reason an extrusion ratio greater than 45 to 1 may take too high extrusion pressure and break the die, while a low ratio smaller than 10 to 1 will use so little pressure that the cast structure of the ingot will not be hot worked enough to give guaranteed mechanical properties. On a high extrusion ratio it is possible to use more than one die openings, thus reducing the ratio so that several sections may be extruded simultaneously and with a favorable extrusion ratio.

Port Ratio

Port ratio plays a vital role in dictating the working life of an aluminum extrusion die, the greater the port ratio the greater is the amount of pressure exerted on the die because of the reduced solid portion of the die surface, thus a region with a stress concentration is more readily subjected to fatigue failure.

3.6 Extrusion Die Life and Parameters/Variables Effecting Die Life

3.6.1 Definition of Die Life

In literature, we find the life of an extrusion die defined in a number of ways, either it is expressed in terms of the number of billets extruded, or the time it takes for the die to fail in hours and in some instances it is defined in terms of the amount of total metal extruded before failure, measured in the number of kilograms. The life of an extrusion die is primarily the duration up till which it performs satisfactorily in terms of the quality of the product being extruded. The approach of total weight of metal extruded through a die will be used in this work to characterize the life of an aluminum extrusion die.

$$\text{Total Weight} = (\text{No. of Pushes}) * (\text{Wt. of a billet})$$

The weight of an individual billet is not a fixed quantity but it depends on the extrusion length and size of the profile needed. Billet weight ranges from 20 to 80 kilograms.

3.6.2 Parameters/Variables Effecting Die Life

The parameters effecting the life of an aluminum extrusion die are mentioned below:

Process Parameters

1. **Speed,** The speed at which the extrusion is carried out.

2. **Temperature,** The working temperature of the process.

3. **Press capacity,** The rated capacity of the extrusion press.

4. **Container diameter,** The diameter of the container in which the billet upsets.

5. **Stretcher capacity,** The pulling force of the stretcher, which pulls the extruded section away from the die, on the run-out table.

Die Material Parameters

1. **Fracture toughness,** The fracture toughness of the extrusion die material(H-13).

2. **Wear resistance,** The wear resistance the die, which is influenced by the surface hardening(nitriding) process.

3. **Stiffness,** The resistance to deflect under working load at elevated temperature.

4. **High temperature strength,** Adequate strength at working temperature.

Product/Die Complexity

1. **Tongue ratio,** It measures the over hanging sections vulnerability under extrusion pressure(Shown in Fig. 1.5).

2. **Perimeter,** It accounts for the surface area generated by the extruded section.

3. **Minimum wall thickness,** The difficulty to extrude thin sections is measured by it(Shown in Fig. 1.5).

4. **Circumscribing circle diameter,** It is a measure of the size of the extruded profile(Shown in Fig. 1.5).

5. **Area,** It reflects the extrusion ratio.

6. **No of cavities,** This gives the number of cavities on a extrusion die.

7. **Weight per unit length,** It is an indicator of the material yield.

Chapter 4

Statistical Analysis of Die Life and its Relationship with Die Complexity

If the time to failure data for the extrusion die is available it can be analysed statistically, and appropriate distribution model can be fitted. The parameters of the model can be investigated to find the trends with respect to various process parameters.

Graphical estimation methods are used in reliability engineering to determine which distribution best fits a set of failure data and to derive interval estimates of the distribution parameters. Two methods are normally followed, one using the probability paper, which have been especially developed for the purpose and the other is through the use of transformed data. Both of these are based upon the cumulative distribution function (c.d.f.)[$F(x)$] of the distribution concerned. The axes of the probability plotting papers are not linear and are generated through transformations in such a way that the true c.d.f. will plot as a straight line. Therefore if a straight line can be fitted to the plotted data on a given probability paper then the data can be characterized by that distribution(for each distribution there is different probability paper. some of these papers are given by Lewis [29]). Further construction permits the distribution parameters to be estimated. Thus reliability data can be evaluated quickly. without a detailed knowledge of the statistical mathematics being necessary. It should be kept in mind that probability plotting methods to derive distribution parameters are only applicable when times to failure are independently and identically distributed (IID). This is usually the case for non-repairable components and systems, which in our case is true for die failures. In the second approach a set of suitably transformed values of F(t), and t are plotted on a linear paper. and straight line is fitted by regression. Correlation coefficient will establish the goodness of fit. and parameters of the distribution can be determined from the slope and intercept of the straight line. This method is convenient for computerized analysis and will be used in this thesis throughout.

4.1 Weibull Distribution

The Weibull distribution is widely used in reliability. It was first presented by Weibull (1939) and its use in reliability studies was discussed by Weibull (1951) [30]. It is a general two-parameter distribution. By adjusting a scale parameter η and a shape parameter β, a variety of shapes can be obtained to fit the experimental data. In particular, the Weibull distribution encompasses both increasing and decreasing hazard rates, and has successfully been used to describe both initial failures as well as wearout failures. When a system is composed of a number of components and failure is due to the weakest element of the system, or when several modes of failure or damage mechanisms are operating simultaneously, the most severe damage manifestation(or extreme value) will cause failure, then time to failure distribution will be weibull.

The hazard function or failure rate for the Weibull distribution is

$$\lambda(t) = \frac{\beta t^{\beta-1}}{\eta^{\beta}} \tag{4.1}$$

in which $\eta > 0$, $\beta > 0$ and $t \geq 0$. *Failure rate* $\lambda(t)$ is a measure of the instantaneous speed of failure. If $\lambda(t) < 1$: it exhibits a decreasing failure rate (infant mortality), if $\lambda(t) = 1$; it corresponds to a constant failure rate (useful life) while if $\lambda(t) > 1$: it depicts a wear out or fatigue phase in the life of a component. The corresponding probability density function $f(t)$ is a measure of the instantaneous failure occurrence, and is given by:

$$f(t) = \frac{\beta t^{\beta-1}}{\eta^{\beta}} exp\left\{-(\frac{t}{\eta})^{\beta}\right\} \tag{4.2}$$

Reliability $R(t)$ measures the probability of survival of a component, and is given by;

$$R(t) = exp\left\{-(\frac{t}{\eta})^{\beta}\right\} \tag{4.3}$$

Cumulative distribution function $F(t)$ measures the probability of failure. and is given by:

$$F(t) = 1 - exp\left\{-(\frac{t}{\eta})^{\beta}\right\} \tag{4.4}$$

The scale parameter or characteristic life η depends upon the mean life, where as shape parameter β reflects the non-dimensional measure of scatter in data.

4.2 Probability Plotting

Probability plotting is a graphical technique whereby observed data and their corresponding empirical cumulative frequencies: $F(t_i) = i/N + 1$ are plotted on suitably constructed probability paper(weibull paper in this case) or a suitable transformation is plotted on a regular graph paper which should a produce linear regression line with a good correlation coefficient [31].

For regression approach the following transformation is needed for the data.

$$R(t) = 1 - F(t) = exp\left\{-(\frac{t}{\eta})^{\beta}\right\} \tag{4.5}$$

Therefore,

$$\frac{1}{1-F(t)} = exp\left\{\frac{t}{\eta}\right\}^{\beta} \tag{4.6}$$

taking double logarithms,

$$ln\left\{ln\left\{\frac{1}{1-F(t)}\right\}\right\} = \beta lnt - \beta ln\eta \tag{4.7}$$

This is a straight line of the form Y = mX + c. In Eq. 4.7 data points Y_i and X_i are obtained by substituting $F(t_i) = i/(N+1)$ and t_i, and are plotted on a linear graph paper for i = 1.2.3.....N. Then a straight line is fitted to this data by regression, the slope β and intercept $-\beta ln\eta$ are found from where η can be determined. This regression approach will be followed in this thesis.

For illustrative purpose the results are plotted in Figures 4.1, 4.2, and 4.3 for the life of three different extrusion dies. In all three cases Weibull model clearly characterize the data extremely well as reflected by high r^2-value. As a matter of fact, a total of 29 different(types) die sets(consisting of failure history of a total of 1400 dies) were analysed this way and each die type was found to be well represented by a Weibull model. These results are summarized in Table 4.1.

From Table 4.1, the following observations are made:

- The correlation coefficient (r^2) being close to unity in each case, depicts the linearity of the plotted data reflecting that weibull model well characterize the time to failure distribution when data pertaining to all modes of failure is combined.

- Almost all dies have $\beta > 1$; indicating dominant wear out or aging phenomena.

The average life of a die which follows a Weibull reliability model for its failure is given by

$$\overline{T} = \eta\Gamma\left\{1+\left\{\frac{1}{\beta}\right\}\right\} \tag{4.8}$$

where,

$\Gamma(x)$ is the gamma function.

The standard deviation of die life is given by:

$$\sigma = \eta\sqrt{\Gamma\left\{1+\frac{2}{\beta}\right\}-\Gamma^2\left\{1+\frac{1}{\beta}\right\}} \tag{4.9}$$

The shape parameter $\beta = f(\sigma/\mu)$ and is illustrated in Fig. 4.4. Fig. 4.4 illustrates relationship between shape parameter β and the coefficient of variation (COV). Note when β increases the coefficient of variation decreases and vice versa.

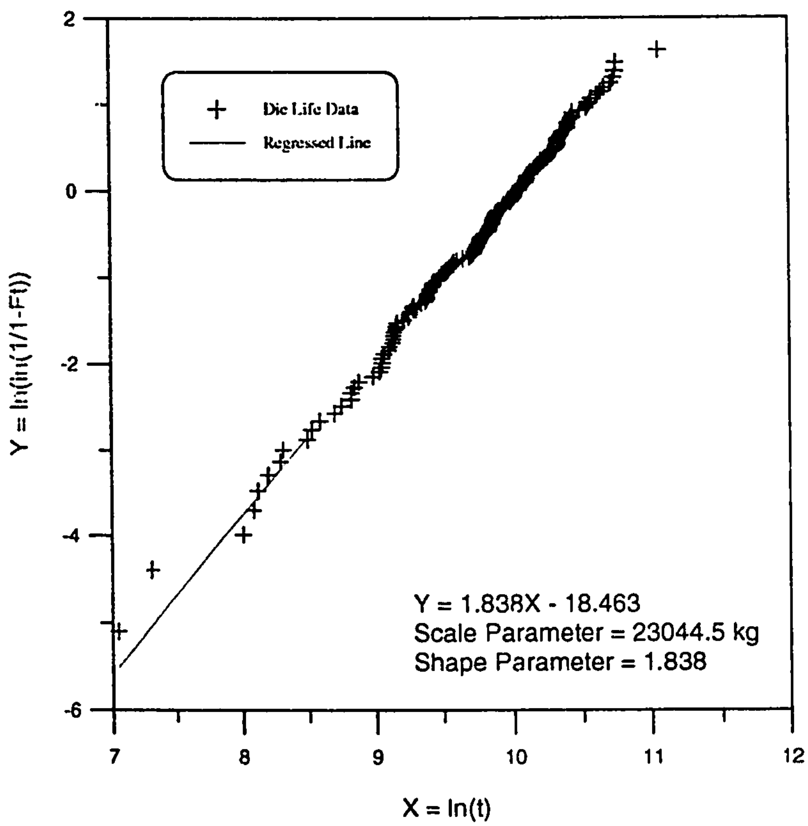


Figure 4.1: Regressed plot to verify the weibull model for H-13 extrusion die (Die No. H9019), time to failure t is measured in kgs of metal extruded and which can be expressed in terms of number of billets. $X = t/w$ (number of pushes); w = weight of a billet [R-sq = 0.9938].

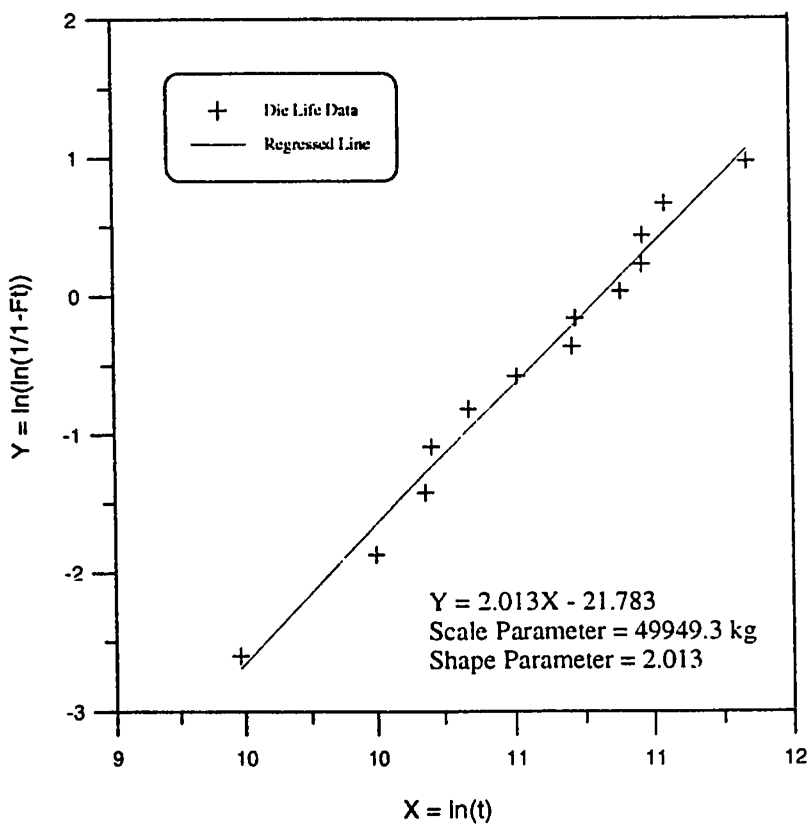


Figure 4.2: Regressed plot to verify the weibull model for H-13 extrusion die (Die No. H9052), time to failure t is measured in kgs. of metal extruded and which can be expressed in terms of number of billets, $N = t/w$ (number of pushes); w = weight of a billet [R-sq = 0.9826] .

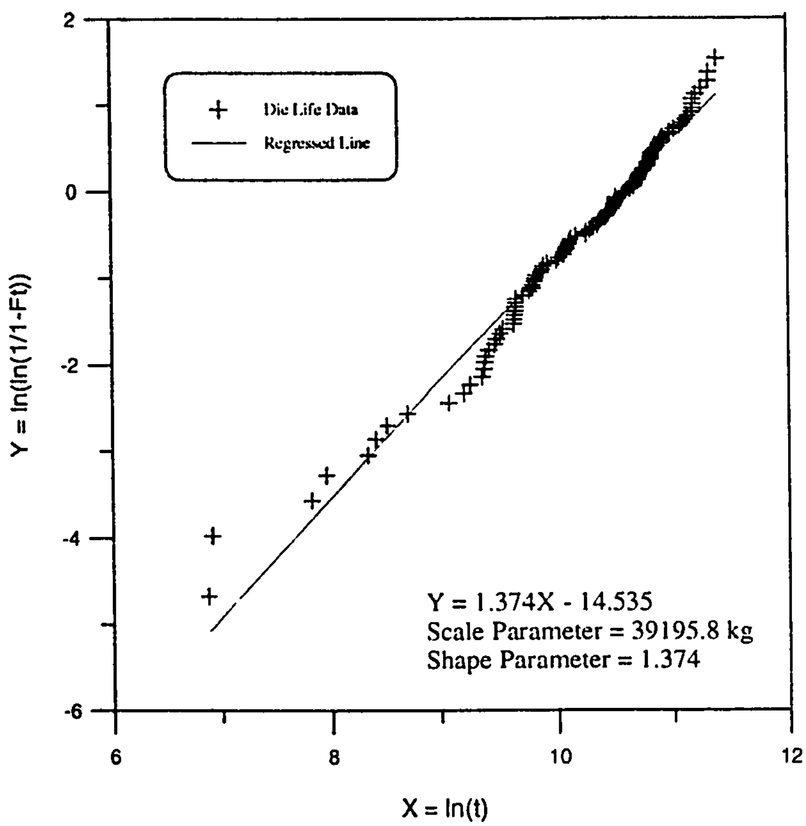


Figure 4.3: Regressed plot to verify the weibull model for H-13 extrusion die (Die No. S9006), time to failure t is measured in kgs. of metal extruded and which can be expressed in terms of number of billets, $N = t/w$ (number of pushes); w = weight of a billet [R-sq = 0.9753].

Table 4.1: Table showing the regressed weibull equation, correlation coefficient(R-sq), scale parameter, shape parameter and average life obtained through regression analysis [Data courtesy of ALUPCO], where Y = ln[ln[1/[1-F]]], X = ln(t) and η (kg) which can be expressed in terms of number of billets, $\eta_N = \eta/\mathrm{w}$ (number of pushes); w = weight of a billet.

S No	Die No.	No of Failures (N)	Regressed Weibull Equation	R-sq Value	Scale Parameter η (kg)	Shape Parameter β	Average Life T (kg)
1	H9028	115	Y = 1.260X-11.649	0.9711	10386.2	1.26	9659.2
2	H4525	53	Y = 1.054X-9.961	0.9748	12694.5	1.054	12419
3	H9049	8	Y = 0.752X-6.822	0.9089	8727.6	0.752	10368.3
4	H9046	23	Y = 1.488X-14.224	0.9205	14196.7	1.488	12826.7
5	H9023	9	Y = 1.052X-10.080	0.9073	14479.2	1.052	14187.9
6	H9050	9	Y = 1.664X-16.374	0.9285	18775.2	1.654	16775.8
7	S9064	7	Y = 1.253X-12.320	0.7058	18694	1.253	17396.6
8	S9017	21	Y = 1.490X-14.897	0.9578	21991	1.49	19866.7
9	H9022	9	Y = 1.109X-11.041	0.8996	21124.8	1.109	20322.1
10	H9019	163	Y = 1.838X-18.463	0.9938	23044.5	1.838	20475.3
11	H1464	31	Y = 1.178X-11.804	0.9197	22448.4	1.178	21227.4
12	H1577	38	Y = 2.014X-20.362	0.9586	24605.6	2.014	21802.3
13	H9026	151	Y = 1.467X-14.827	0.9845	24443.7	1.467	22131.3
14	H1553	13	Y = 1.587X-16.334	0.9643	29450.8	1.587	26724.4
15	H9062	13	Y = 2.477X-25.813	0.8988	33536.8	2.477	29750.5
16	H5178	43	Y = 1.812X-19.100	0.993	37842.8	1.812	33638.5
17	H9009	73	Y = 1.875X-19.827	0.9829	39058	1.875	34675.7
18	H9057	72	Y = 1.606X-16.978	0.9806	39030	1.606	34978.7
19	H9008	104	Y = 1.866X-19.773	0.9936	39917.4	1.866	35441.1
20	S9006	107	Y = 1.374X-14.535	0.9753	39195.8	1.374	35828.9
21	S9070	53	Y = 1.754X-18.610	0.9796	40553.9	1.754	36112.4
22	H9032	141	Y = 1.631X-17.365	0.9604	41949.4	1.631	37544.7
23	S1466	16	Y = 1.262X-13.442	0.9586	42088	1.262	39116.6
24	H9052	13	Y = 2.013X-21.783	0.9826	49949.3	2.013	44260.1
25	S1465	32	Y = 1.269X-13.672	0.9046	47993.3	1.269	44537.8
26	S9031	40	Y = 1.313X-14.292	0.8804	53590.5	1.313	49383.6
27	S9030	9	Y = 1.677X-18.358	0.9496	56637.5	1.677	50577.3
28	S1113	9	Y = 1.173X-12.793	0.9068	54469.7	1.173	51544.7
29	S9029	17	Y = 1.949X-21.827	0.9635	73084.7	1.949	64804.2

4.3 Die Complexity

Aluminum extrusion flat-faced dies are mainly classified into two groups; dies for solid shapes and dies for hollow profiles. The former include those dies which produce solid sections, including round, hexagonal, square, flat, L-shaped, etc., profiles, while the later include dies producing hollow sections having square, rectangular or complex shapes mainly used for structural purposes. Extrusion shapes of aluminum alloys are generally characterized according to geometric size and complexity. It is reasonable to expect that a die with least complexity should have a longer life. and as the die complexity increases, the corresponding average life decreases. Similarly it is anticipated that there is some type of relationship between die complexity and standard deviation of life. As a consequence of this the overall reliability of die will be a function of die complexity. To explore the behavior of reliability function as a function of die complexity, it is necessary to study the behavior of weibull distribution parameter η (or average life) and β (or coefficient of variation) with respect to various indices of die complexity available from literature.

4.3.1 Literature Definitions.

In literature, three acceptable definitions exist that define the complexity of the die. These include shape factor, form factor and F_{form} index [32].

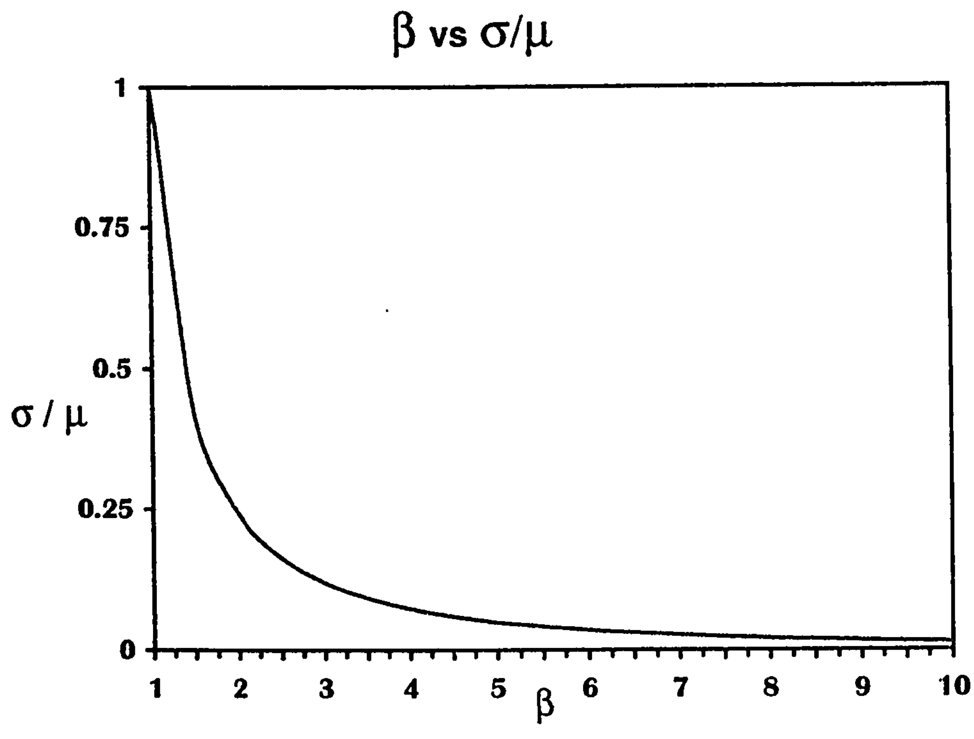


Figure 4.4: Plot showing the relationship between β and $COV = \sigma/\mu$.

Shape factor.

It is the ratio of the perimeter to the profile weight per unit length [33], (later on it will also be referred as Comp. 1) and is given by:

$$Comp\ 1 = Shapefactor = \frac{Perimeter}{Weight} \tag{4.10}$$

This factor measures the amount of surface generated per unit weight of metal extruded. The shape factor affects the production rate as well as the cost of manufacturing and maintaining the dies. It is used by many extruders as a basis for pricing and provides the designer with a means of comparing the relative complexity of alternate designs.

Form factor.

In extrusion, metal tends to flow more slowly at die locations that are far away from the axis of the billet. Therefore, the larger the circumscribing circle diameter (CCD), the more control required to maintain the dimensions of the extruded shape. Special care is needed in extruding large and thin shapes, especially those with thin portions near the periphery of the die. The form factor was devised keeping the above mentioned difficulties in mind [32], (later on it will also be referred as Comp. 2) and is defined as:

$$Comp\ 2 = Formfactor = \frac{CCD}{t_{min}} \tag{4.11}$$

Which is the ratio of the circumscribing circle diameter(CCD) to the minimum wall thickness of the profile. Hence it shows that the size of the profile is one of the factors that describe the complexity of the shape.

$\underline{F_{form}.}$

Occasionally we see aluminum shapes with semi-hollow details having protruded legs. These profiles give an additional difficulty in terms of their strength, the die of such shapes carry over-hanging sections which are usually very weakly supported at their roots. These details are known as tongues and the severity of their complexity is defined by *tongue ratios*(see Fig 1.5). Also, whenever dealing with a semi-hollow shape there the matter of external and internal perimeter of the shape is encountered, which also effects the overall complexity of the die profile. Hence F_{form} index was devised [32], (later on it will also be referred as Comp. 3) and is given by:

$$Comp\ 3 = F_{form} = \frac{10A}{D_u log A\sqrt{U_o + aU_i}} \tag{4.12}$$

where A is the cross-sectional area of the profile in (mm^2), D_u is the CCD in (mm), U_o is the outside perimeter of the section (mm) and U_i is the inside perimeter of the semi-hollow and hollow sections (mm).The factor a measures the tongue ratio and it ranges from 1 to 2.

Table 4.2 provide the value of $Shapefactor, Formfactor$ and F_{form} for each of the die analyzed in Table 4.1.

4.4 Die Life Distribution Parameters and Complexity Correlation

It is a well recognized fact in the extrusion industry that the more complex the die profile the lesser is the life. Keeping this fact in mind, the task of correlating the die life parameters with the die complexity is under taken. The procedure is as follows;

- First of all the Weibull parameters of the die failure model are evaluated by probability plotting as shown in Fig. 4.1, 4.2, and 4.3.
- Then the shape and scale parameter are plotted against the die complexity and their correlation is determined, as shown in Fig. 4.5, 4.6, 4.7, 4.8, 4.9, and 4.10 for all three measures of die complexity, $Shapefactor, Formfactor\ and\ F_{form}$ (i.e., Comp. 1, Comp. 2, and Comp. 3 respectively).
- With the help of the correlation which represents die life scale and shape parameters as a function of the profile complexity; the model parameters are evaluated for any individual die.
- Finally the evaluated parameters are put into Eq. 4.1, 4.2, 4.3 and 4.4 to find the respective reliability or related functions.

- The comparison between the functions evaluated through the complexity correlation, fitted model and empirical distribution(failure data) is shown in Fig. 4.11, 4.12, 4.13, 4.14, 4.15 and 4.16 for dies of different complexity.

- These models, and data represent failure due to all three modes of failure.

- The approach was repeated for each one of the dies in the Table 4.2. However. the results for only H-9019, H-9008 and H-9052 dies are selected for presentation.

Observing Fig. 4.11, 4.12. 4.13. 4.14, 4.15 and 4.16, we conclude that the Form Factor (Complexity 2) gives acceptable reliability prediction in some cases, but in general the prediction is not dependable, and no definition of complexity obtained from literature seems reasonable. Looking at Table 4.2 and Fig. 4.5 to 4.10, one observes that in general we do not observe an increase in life as complexity decreases. Hence the reliability prediction done using the correlation between die life and literature complexity definitions, doesn't give good results. One reason for the unacceptable results is that, the complexity definitions existing in literature are deficient because they do not completely account for the extruded profile complexity. So arise the need of new comprehensive die complexity definition which when used for reliability prediction will give better results, and will also satisfy the expected result that as complexity increases, average life decreases in a monotonical fashion.

Table 4.2: Different literature complexities of large number of dies. [where Y = ln[ln[1/[1-F]]], X = ln(t) and η (kg) which can be expressed in terms of number of billets, $\eta_N = \eta$/w (number of pushes); w = weight of a billet.]

S.No.	Die Number	Regressed Weibull Equation	Scale Parameter η (kg)	Shape Parameter β	Complexity Factors			Average Life Kg
					Shape Factor	Form Factor	F Form	
					Comp. 1	Comp. 2	Comp. 3	
1	H9028	Y = 1.260X-11.649	10386.2	1.26	0.57	83.85	0.448	9659.2
2	H9049	Y = 0.752X-6.822	8727.6	0.752	0.74	120	0.275	10368.3
3	H4525	Y = 1.054X-9.961	12694.5	1.054	0.55	97.31	0.31	12419
4	H9046	Y = 1.488X-14.224	14196.7	1.488	0.74	89.5	0.42	12826.7
5	H9023	Y = 1.052X-10.080	14479.2	1.052	0.47	85.33	0.49	14187.9
6	H9050	Y = 1.664X-16.374	18775.2	1.664	0.49	70.77	0.58	16775.8
7	S9064	Y = 1.253X-12.320	18694	1.253	0.49	96.15	0.34	17396.6
8	S9017	Y = 1.490X-14.897	21991	1.49	0.57	92.31	0.48	19866.7
9	H9022	Y = 1.109X-11.041	21124.8	1.109	0.54	71.54	0.532	20322.1
10	H9019	Y = 1.838X-18.463	23044.5	1.838	0.57	93.7	0.39	20475.3
11	H1464	Y = 1.178X-11.804	22448.4	1.178	0.47	84.3	0.4	21227.4
12	H1577	Y = 2.014X-20.362	24605.6	2.014	0.6	100	0.24	21802.3
13	H9026	Y = 1.467X-14.827	24443.7	1.467	0.57	117.7	0.27	22131.3
14	H1553	Y = 1.587X-16.334	29450.8	1.587	0.47	84.4	0.39	26724.4
15	H9062	Y = 2.477X-25.813	33536.8	2.477	0.5	115.4	0.254	29750.5
16	H5178	Y = 1.812X-19.100	37842.8	1.812	0.57	115.4	0.27	33638.5
17	H9009	Y = 1.875X-19.827	39058	1.875	0.57	109.8	0.3	34675.7
18	H9057	Y = 1.606X-16.978	39030	1.606	0.56	114.6	0.25	34978.7
19	H9008	Y = 1.866X-19.773	39917.4	1.866	0.57	114.6	0.27	35441.1
20	S9006	Y = 1.374X-14.535	39195.8	1.374	0.54	81.48	0.589	35828.9
21	S9070	Y = 1.754X-18.610	40553.9	1.754	0.53	92.6	0.52	36112.4
22	H9032	Y = 1.631X-17.365	41949.4	1.631	0.55	117.9	0.29	37544.7
23	S1466	Y = 1.262X-13.442	42088	1.262	0.51	83.6	0.62	39116.6
24	H9052	Y = 2.013X-21.783	49949.3	2.013	0.46	134.2	0.31	44260.1
25	S1465	Y = 1.269X-13.672	47993.3	1.269	0.51	83.6	0.588	44537.8
26	S9031	Y = 1.313X-14.292	53590.5	1.313	0.53	110.2	0.3	49383.6
27	S9030	Y = 1.677X-18.358	56637.5	1.677	0.56	103.8	0.308	50577.3
28	S1113	Y = 1.173X-12.793	54469.7	1.173	0.52	94.3	0.24	51544.7
29	S9029	Y = 1.949X-21.827	73084.7	1.949	0.62	110	0.224	64804.2

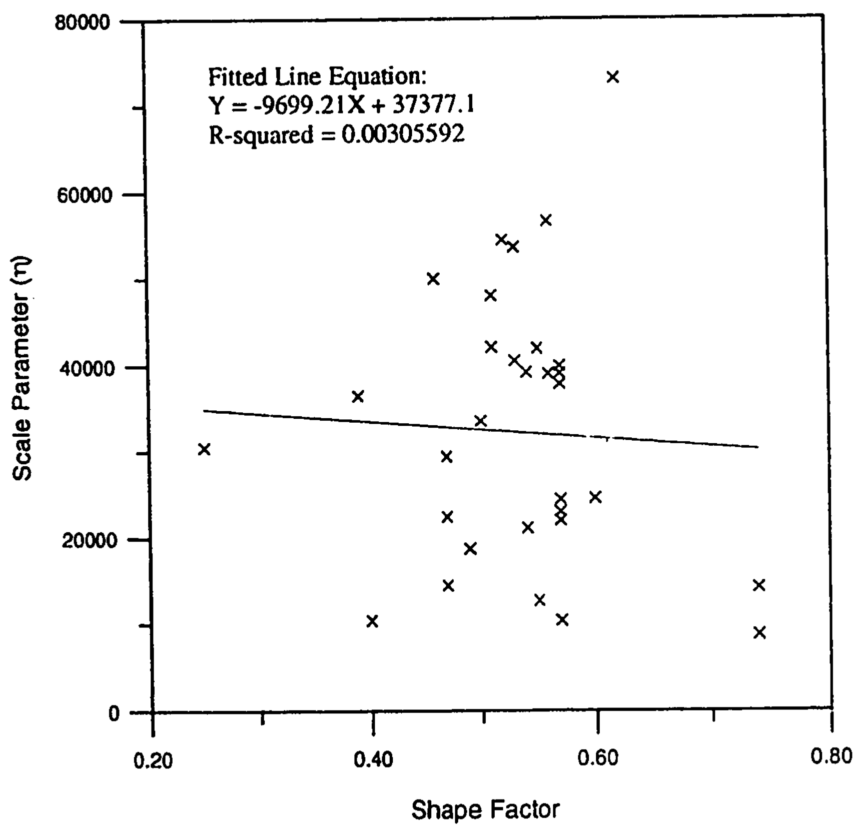


Figure 4.5: Graph evaluating the relationship between scale parameter and the die complexity(Shape Factor), η is in kg, Y = η and X = Shape Factor.

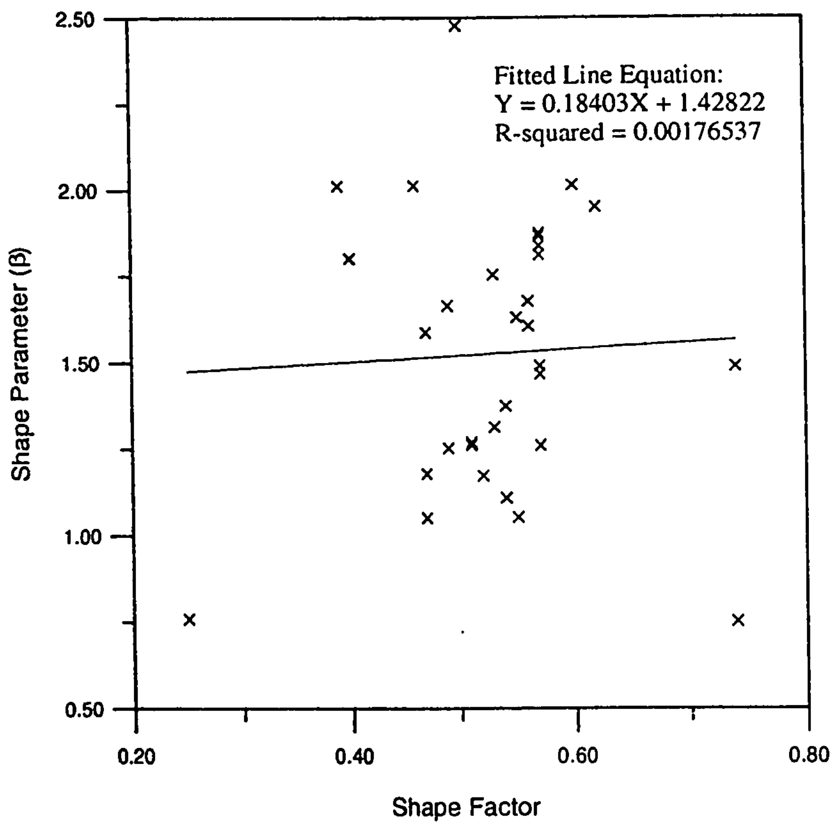


Figure 4.6: Graph evaluating the relationship between shape parameter and the die complexity(Shape Factor), Y = β and X = Shape Factor.

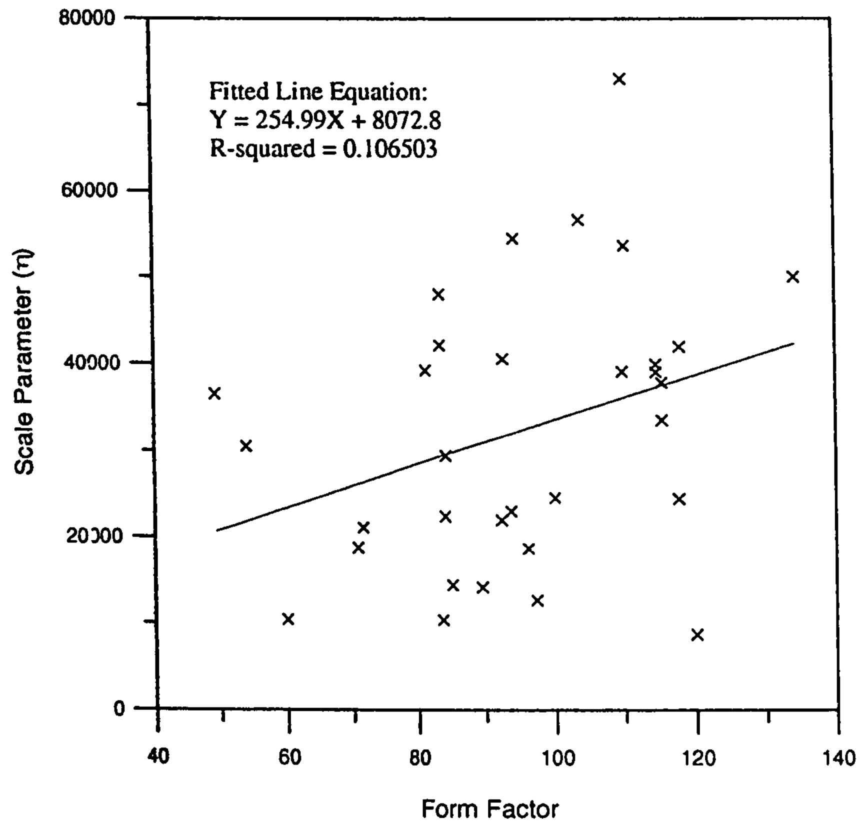


Figure 4.7: Graph evaluating the relationship between scale parameter and the die complexity(Form Factor), η is in kg, $Y = \eta$ and $X =$ Form Factor.

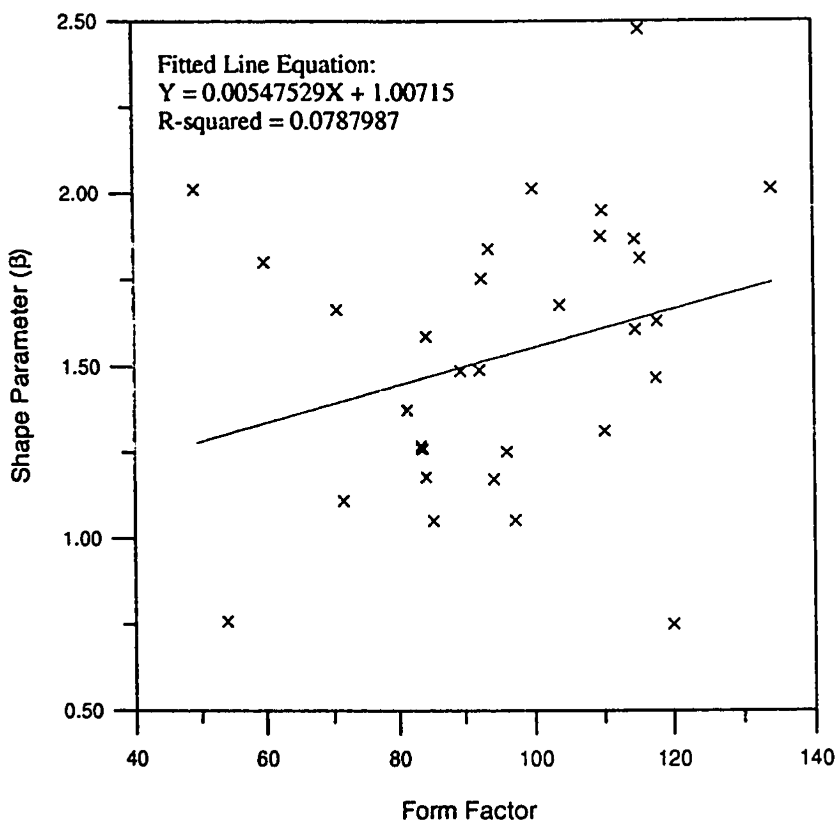


Figure 4.8: Graph evaluating the relationship between shape parameter and the die complexity(Form Factor), Y = β and X = Form Factor.

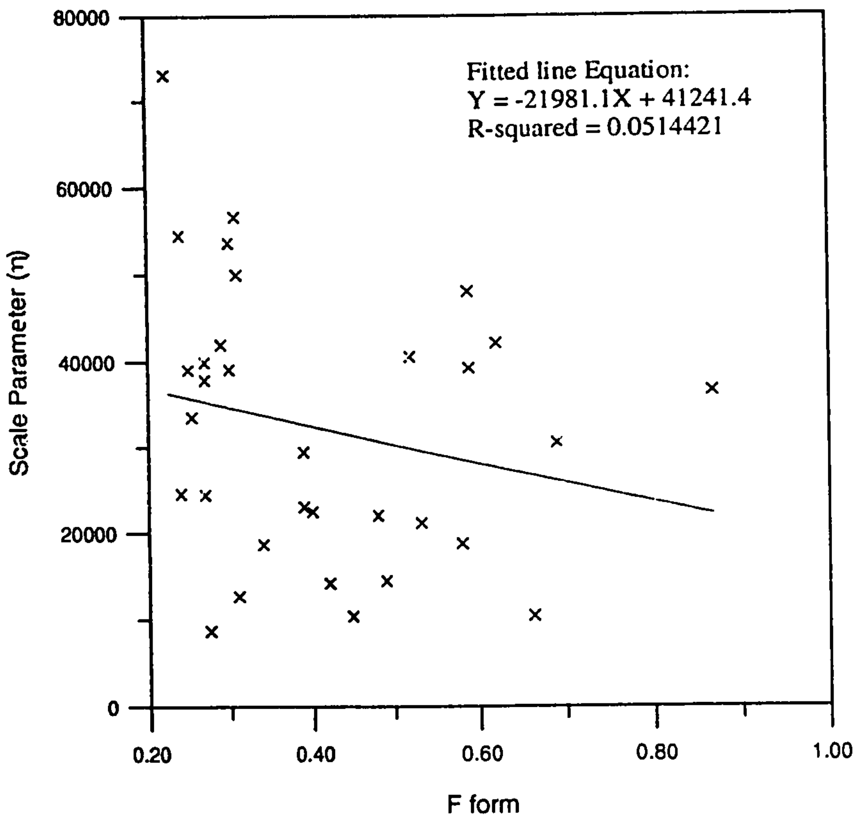


Figure 4.9: Graph evaluating the relationship between scale parameter and the die complexity(F_{form}), η is in kg, $Y = \eta$ and $X = F_{form}$.

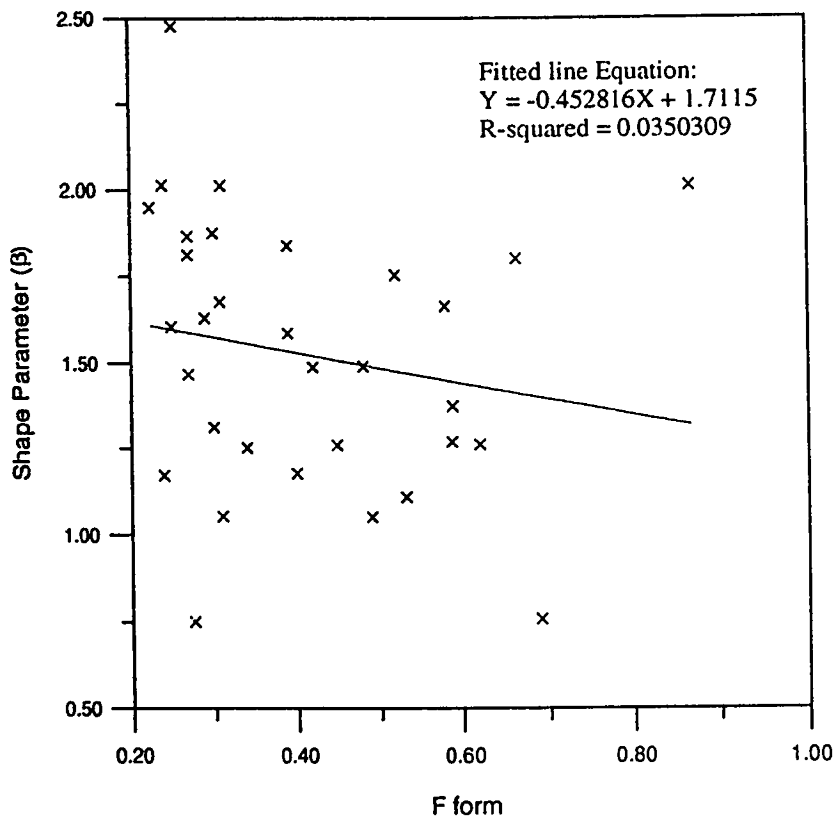


Figure 4.10: Graph evaluating the relationship between shape parameter and the die complexity(F_{form}), Y = β and X = F_{form}.

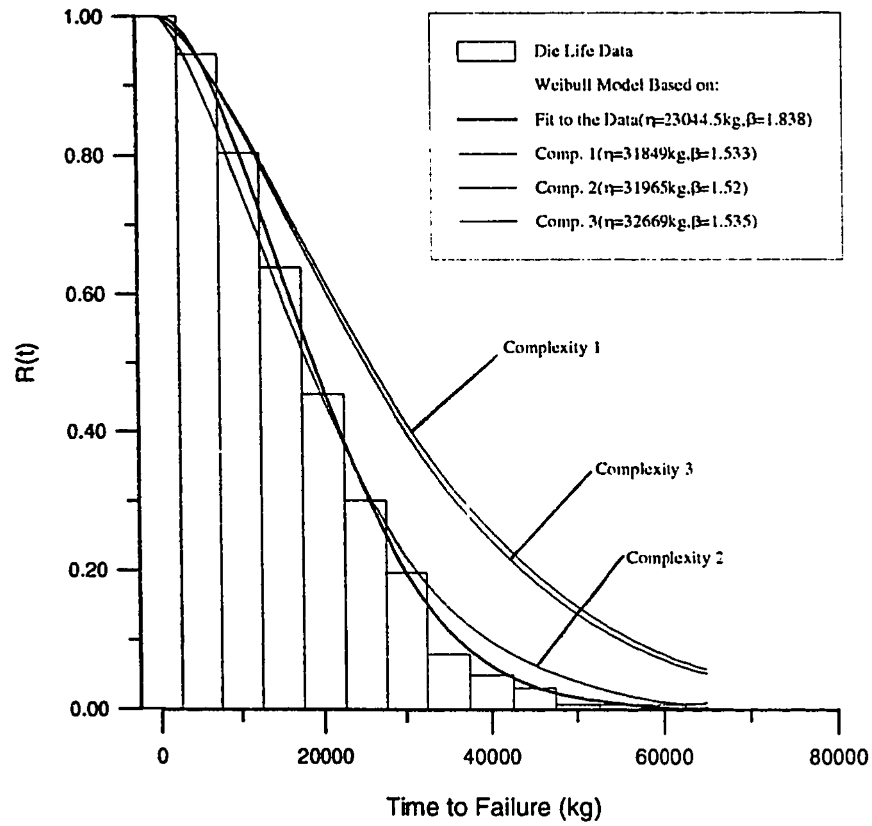


Figure 4.11: Reliability comparison obtained through different literature complexity definitions (Die No.H9019) [Comp. 1 = 0.57, Comp. 2 = 93.7, and Comp. 3 = 0.39].

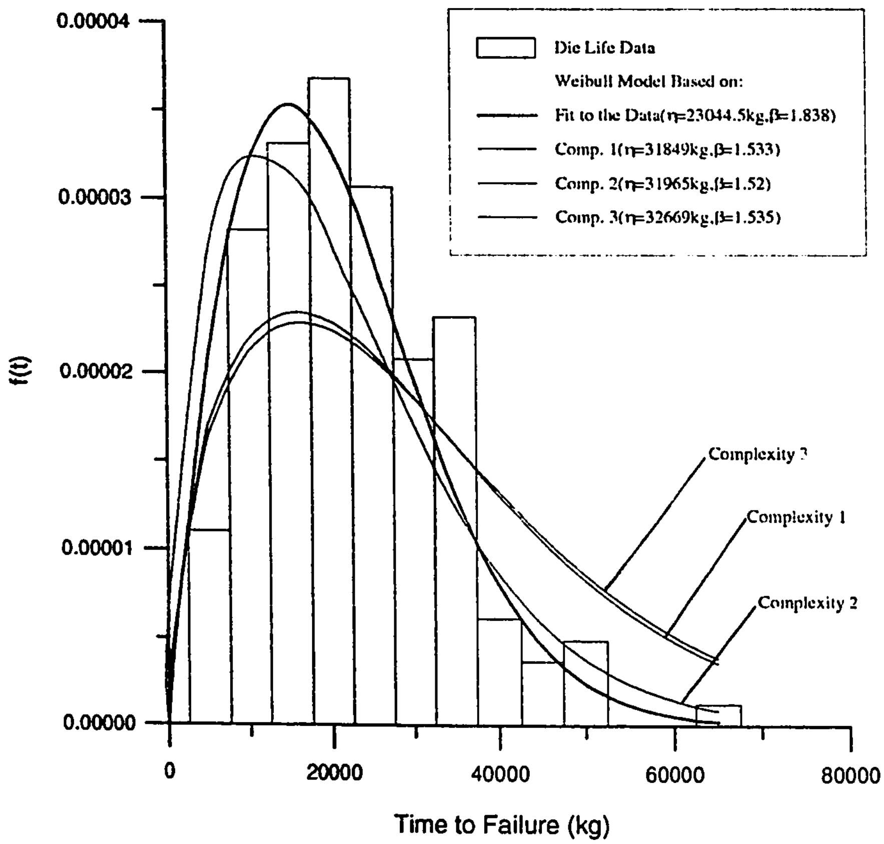


Figure 4.12: Frequency distribution comparison obtained through different literature complexity definitions (Die No.H9019) [Comp. 1 = 0.57, Comp. 2 = 93.7, and Comp. 3 = 0.39].

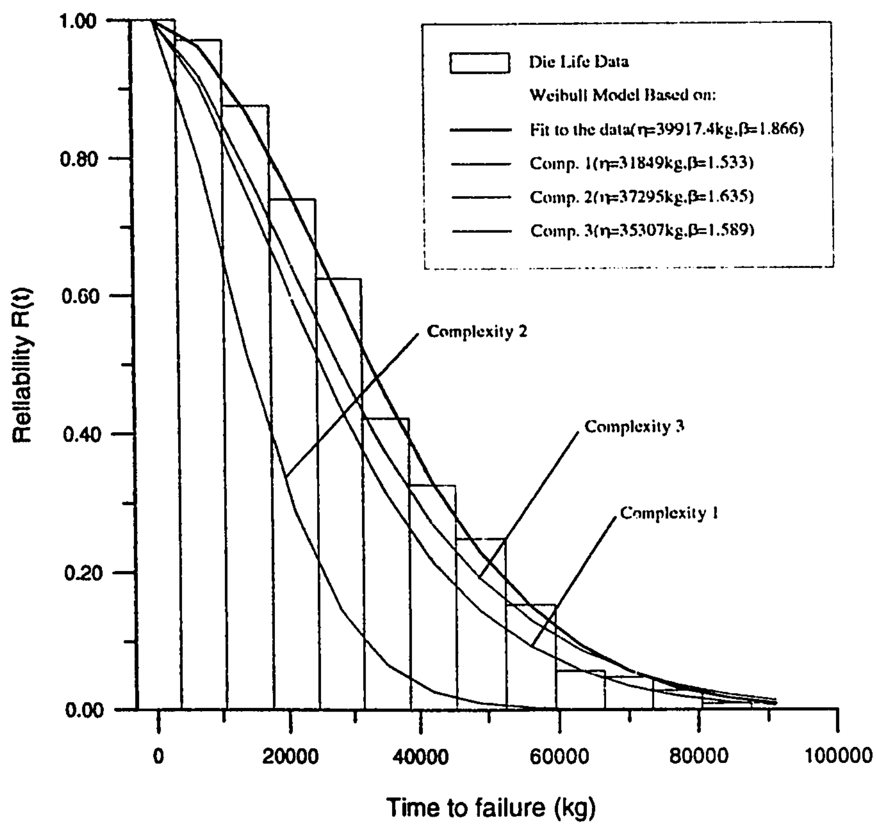


Figure 4.13: Reliability comparison obtained through different literature complexity definitions (Die No.H9008) [Comp. 1 = 0.57, Comp. 2 = 114.6, and Comp. 3 = 0.27].

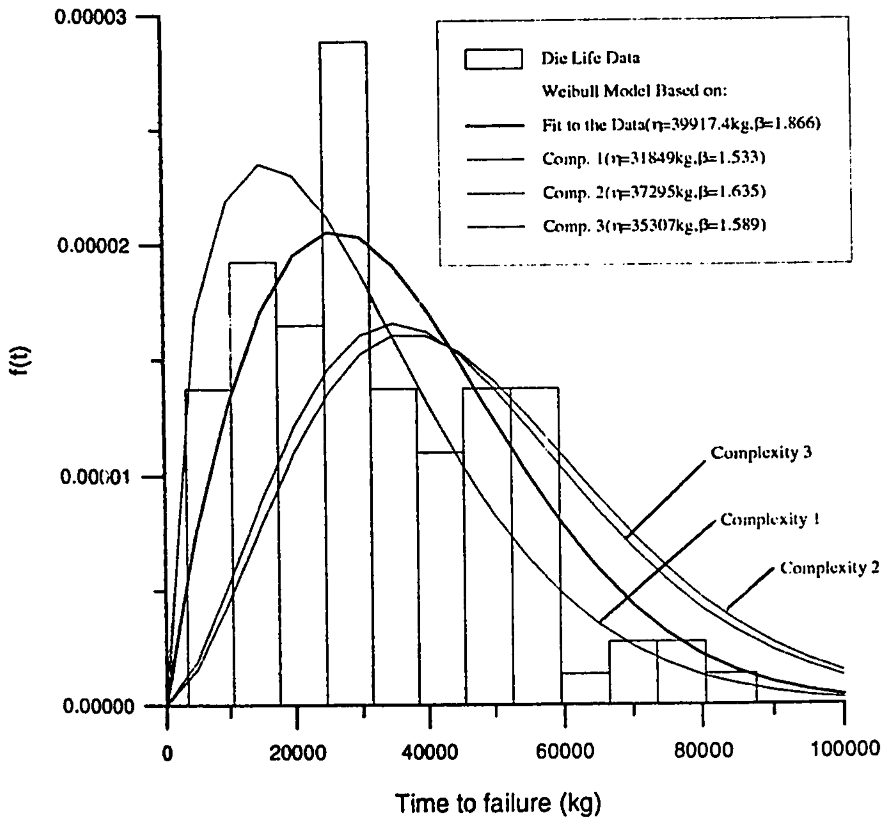


Figure 4.14: Frequency distribution comparison obtained through different literature complexity definitions (Die No.H9008) [Comp. 1 = 0.57, Comp. 2 = 114.6, and Comp. 3 = 0.27].

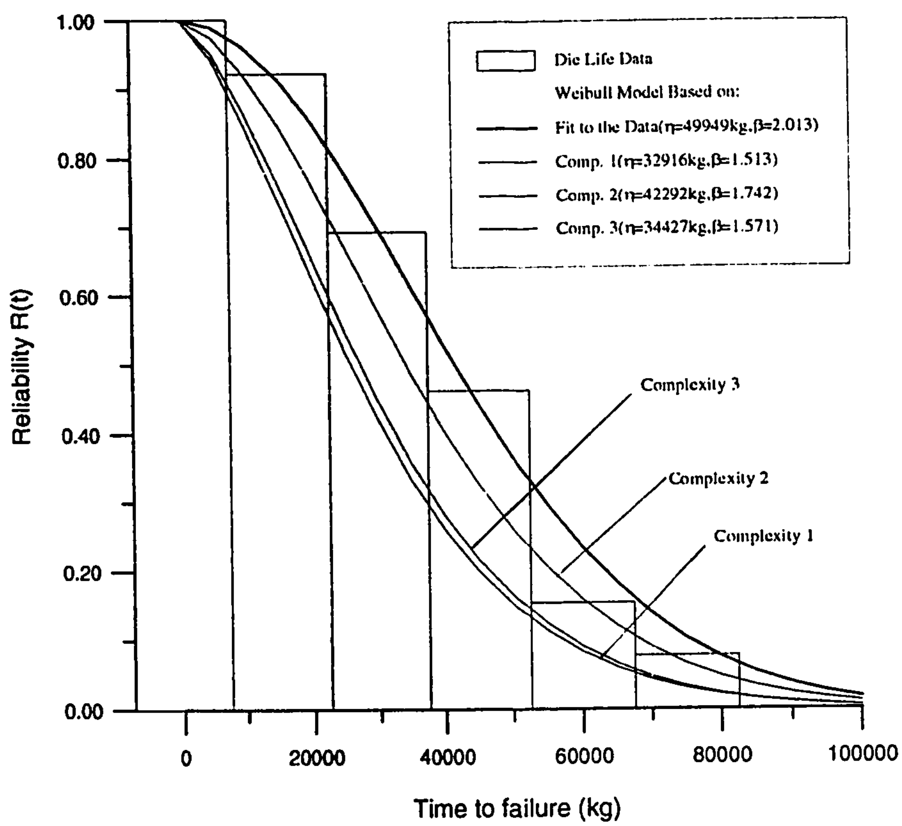


Figure 4.15: Reliability comparison obtained through different literature complexity definitions (Die No.H9052) [Comp. 1 = 0.46, Comp. 2 = 134.2, and Comp. 3 = 0.31].

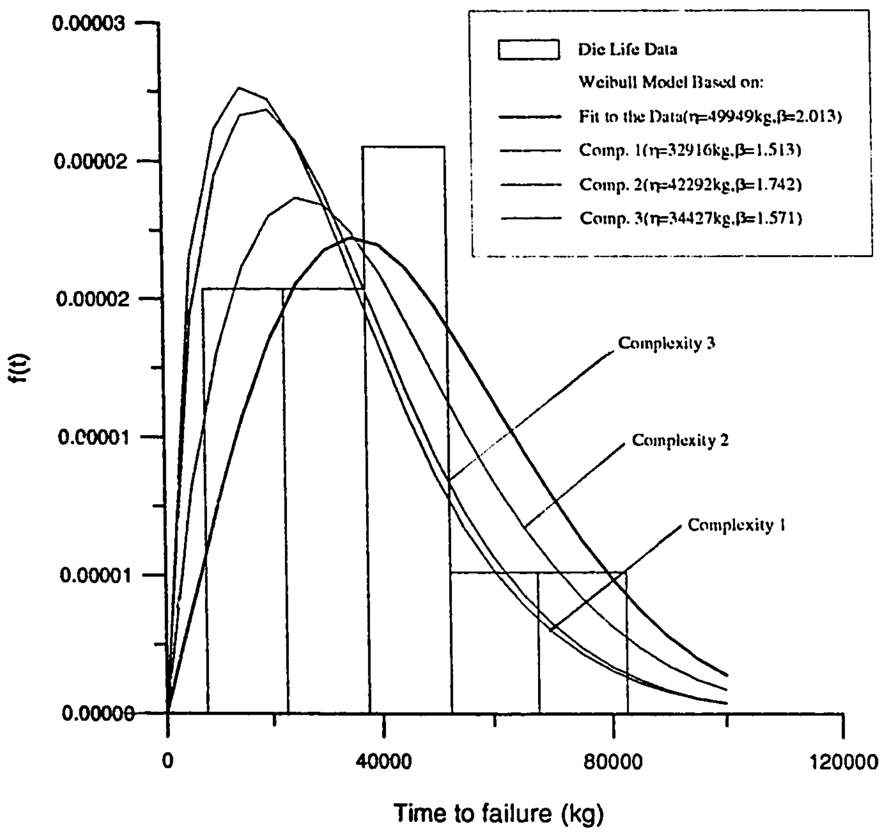


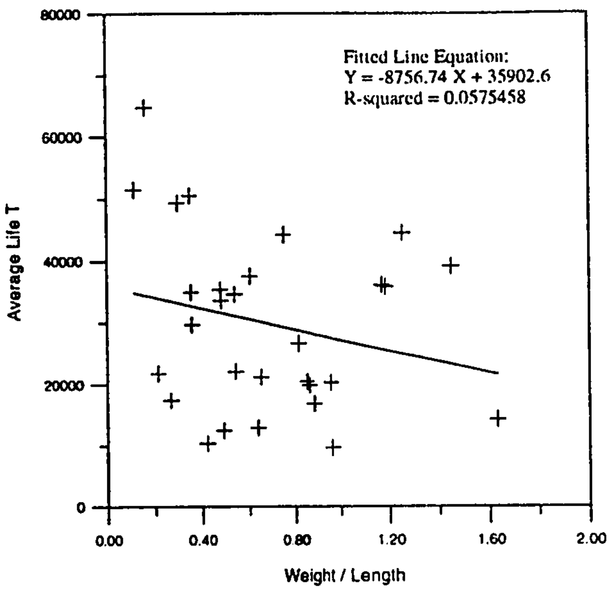
Figure 4.16: Frequency distribution comparison obtained through different literature complexity definitions (Die No.H9052) [Comp. 1 = 0.46, Comp. 2 = 134.2, and Comp. 3 = 0.31].

4.5 Proposed Die Complexity Factor

Each of the above complexity definitions deals with a few of the numerous factors which dictate the over all complexity. There is a need for a comprehensive complexity definition which incorporates all known factors such as given in chapter 3(section 3.6.2). affecting the die life. If more variables are included, then a better complexity factors can be developed. There are basically eight main factors influencing the relative complexity of the die. which include [34]:

- The weight per unit length. W/L = X_1
- The circumscribing circle diameter. CCD = X_2
- The profile perimeter. P = X_3
- The weighted perimeter. $W_p = X_4$
- The minimum wall thickness of the profile, $t_{min} = X_5$
- The profile area. A = X_6
- The number of profile cavities. N = X_7
- The press container diameter, C.D. = X_8

An exploratory study was conducted to examine the nature of relationship of average die life with different critical variables described above. This exploratory study will provide some clue to hypothesis an appropriate regression model to characterize $\overline{T} = f(X_1, X_2, ...X_8)$ Fig. 4.17, 4.18, 4.19, and 4.20. show the linear dependence of the different variables with the average die life $\overline{T}$. Similarly Log Log plots between the variables involved and the average die life $\overline{T}$ are shown in Figures. 4.21, 4.22, 4.23, and 4.24. Over all Log Log plots were slightly better correlated then the linear or Semi Log relationship(not shown). Based upon these observations a large number of multiple regression models were proposed, and their predicted and actual values were compared. After an intensive regression modelling the following model(described in next section). was narrowed down as the best model.



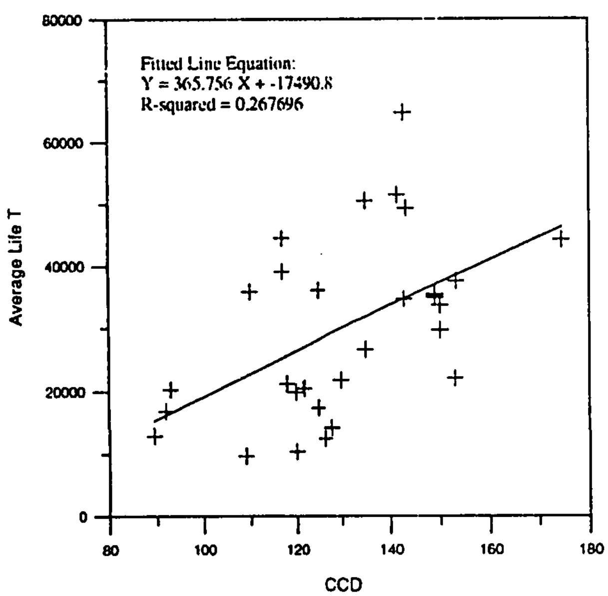


Figure 4.17: Plots showing the dependence of Average Life $\overline{T}$ (kg.) with Weight per unit length (Kg/m) and Circumscribing Circle Diameter (mm).

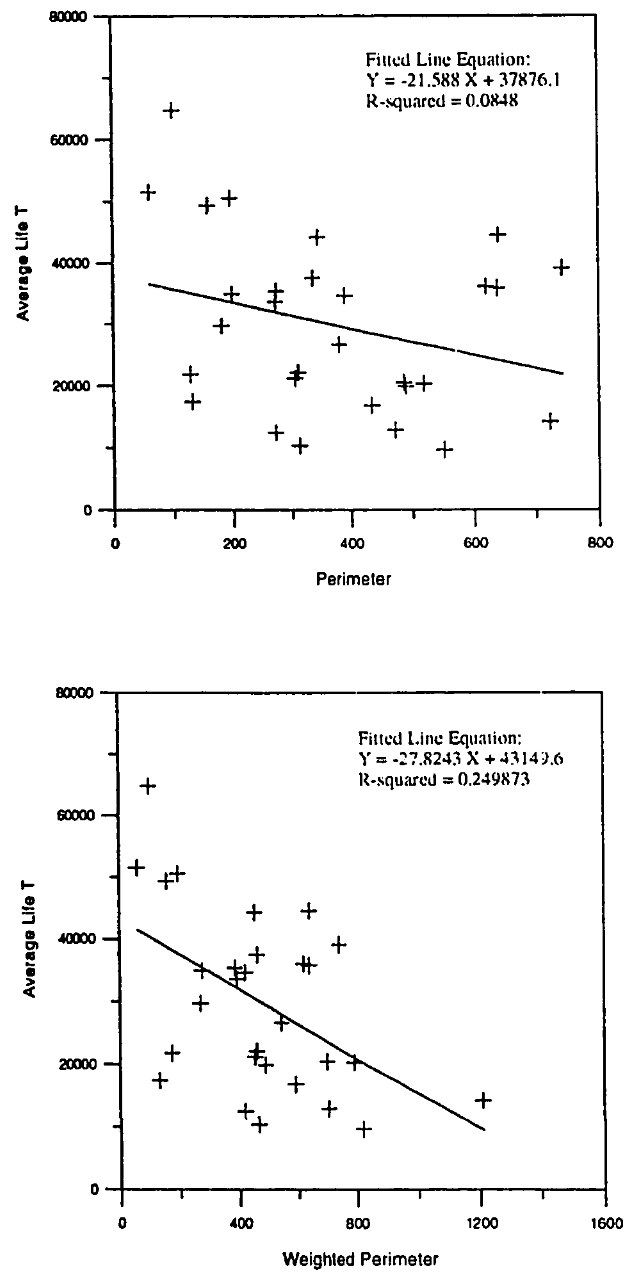


Figure 4.18: Plots showing the dependence of Average Life $\overline{T}$ (kg.) with Perimeter (mm) and Weighted Perimeter (mm).

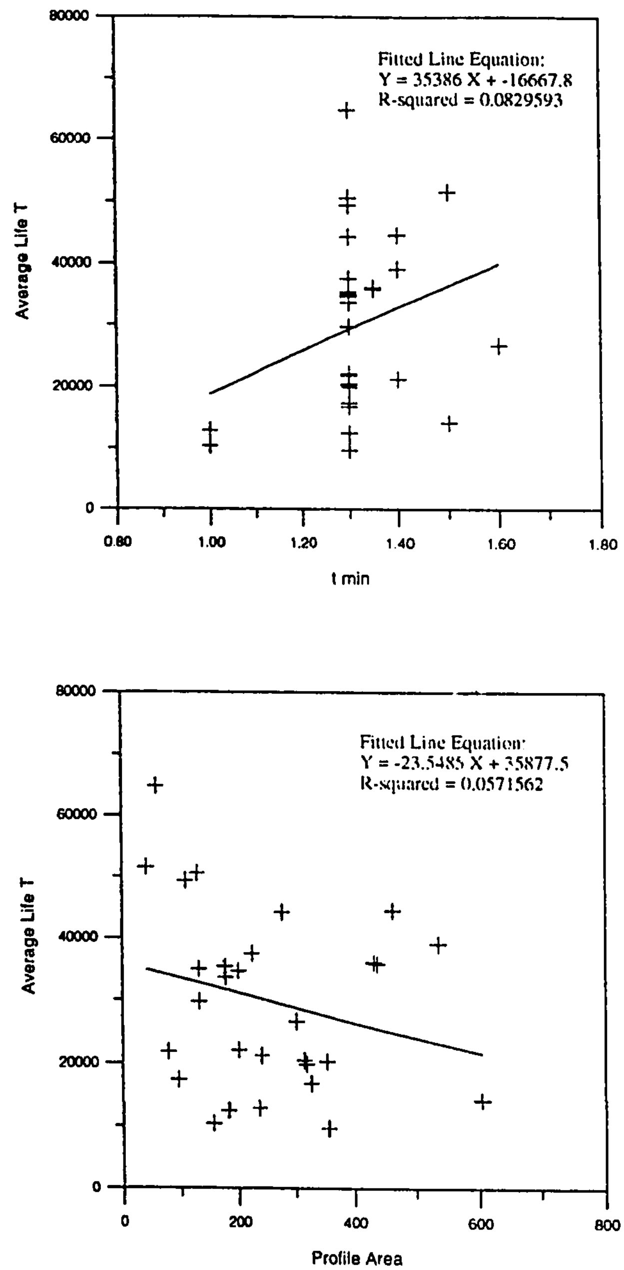


Figure 4.19: Plots showing the dependence of Average Life $\overline{T}$ (kg.) with Minimum Wall Thickness (mm) and Profile Area (sq-mm).

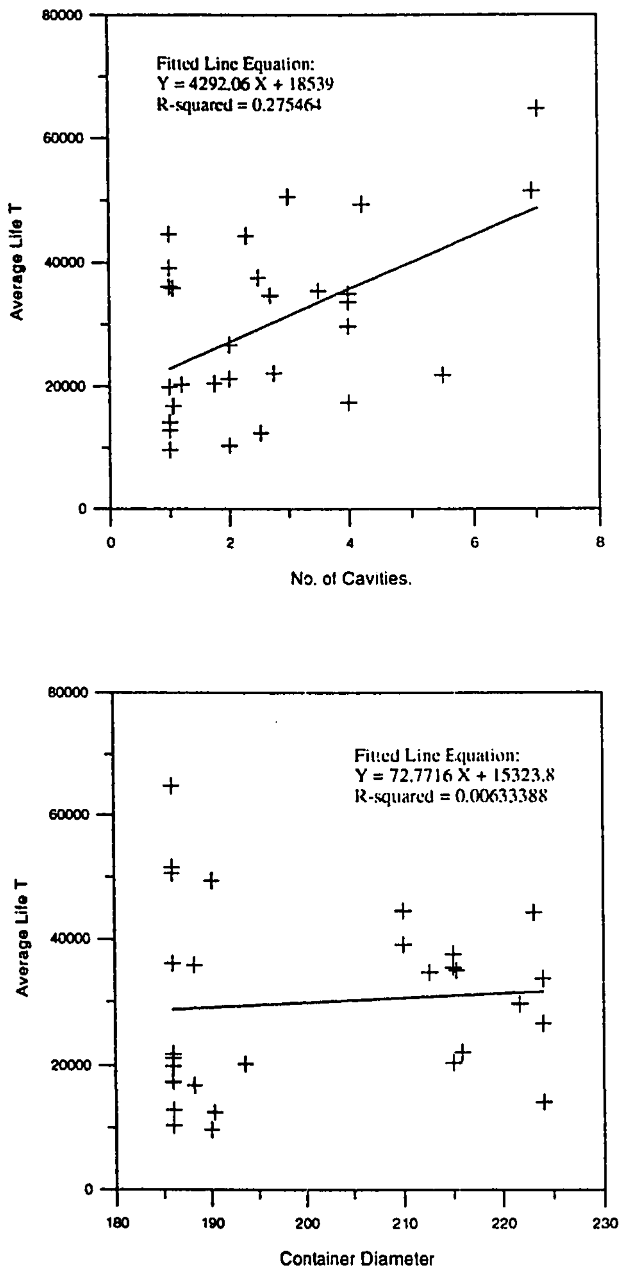
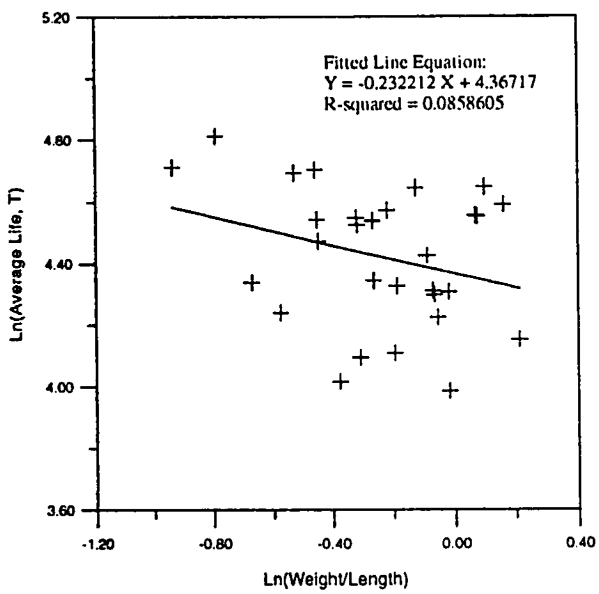


Figure 4.20: Plots showing the dependence of Average Life $\overline{T}$ (kg.) with Number of Cavities and Container Diameter (mm).



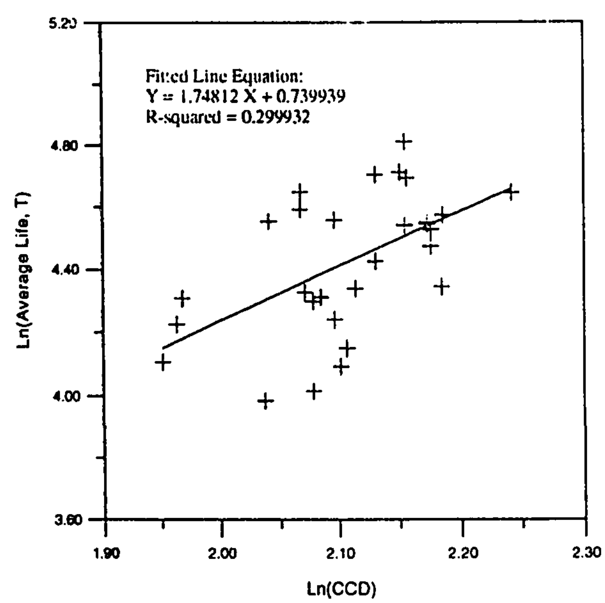
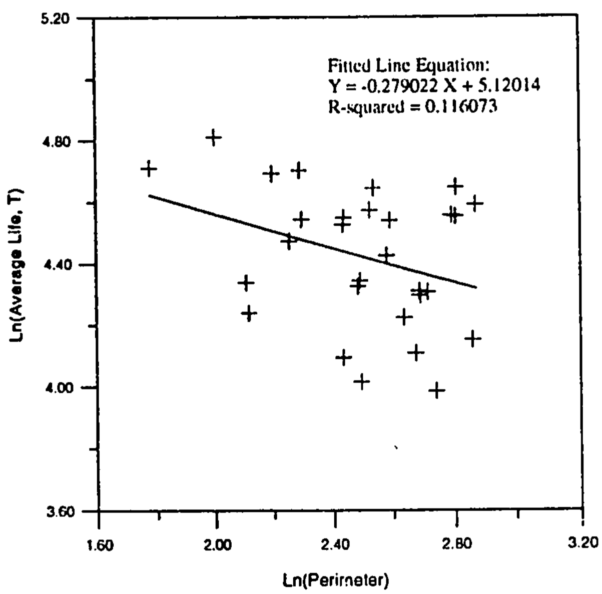


Figure 4.21: LogLog Plots showing the dependence of Average Life $\overline{T}$ (kg.) with Weight per unit length (Kg/m) and Circumscribing Circle Diameter (mm).



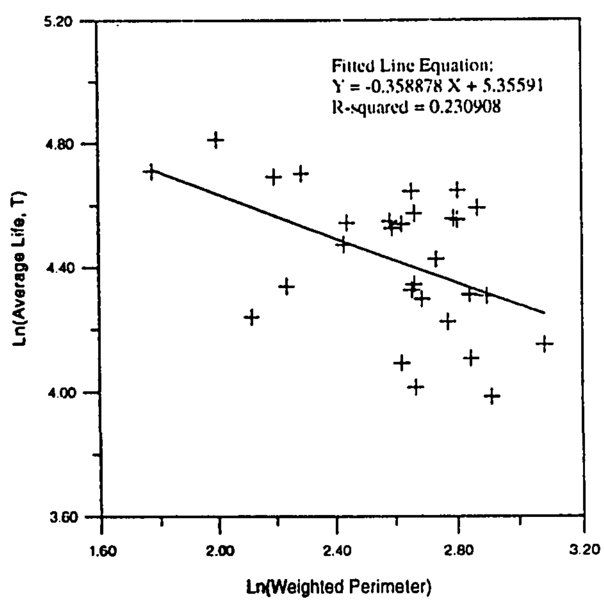
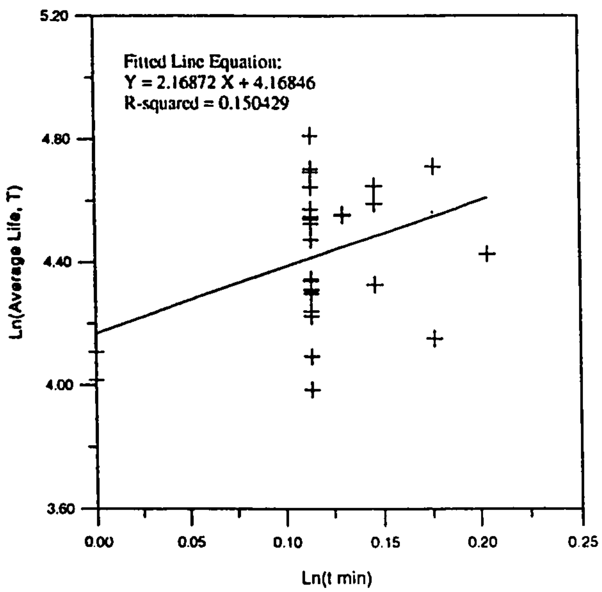


Figure 4.22: LogLog Plots showing the dependence of Average Life $\overline{T}$ (kg.) with Perimeter (mm) and Weighted Perimeter (mm).



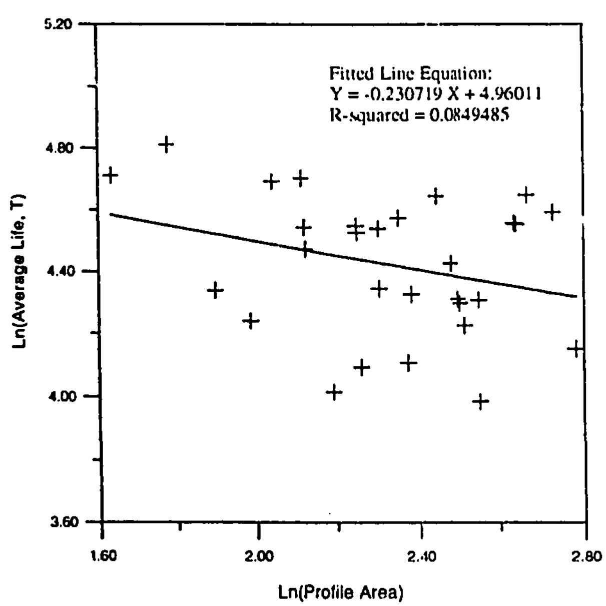
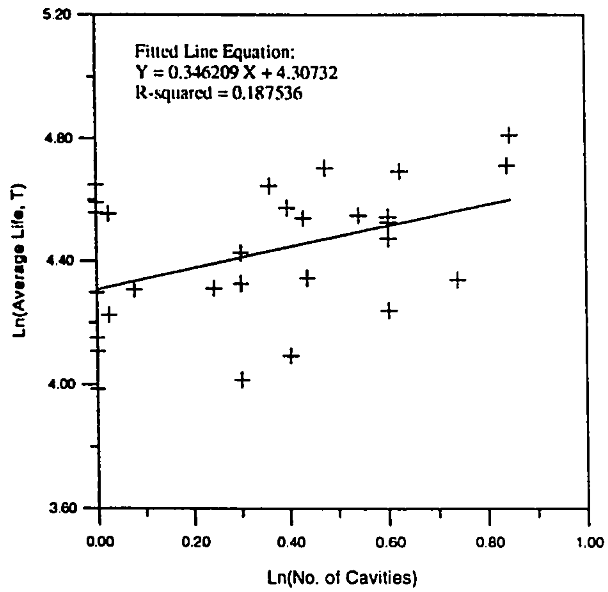


Figure 4.23: LogLog Plots showing the dependence of Average Life $\overline{T}$ (kg.) with Minimum Wall Thickness (mm) and Profile Area (sq-mm).



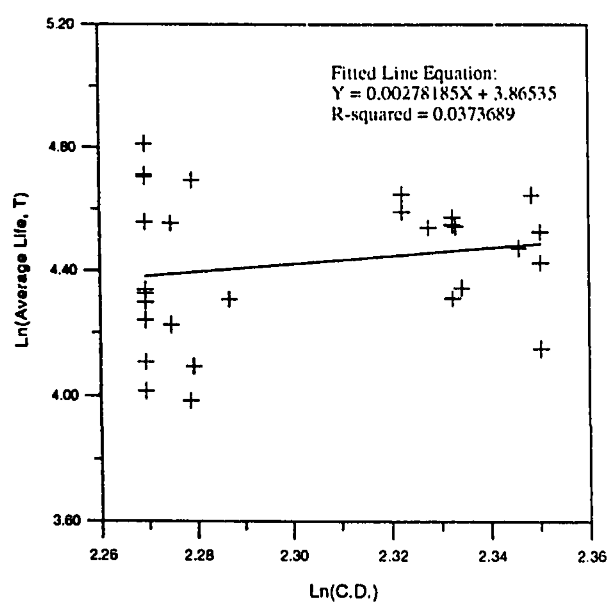


Figure 4.24: LogLog Plots showing the dependence of Average Life $\overline{T}$ (kg.) with Number of Cavities and Container Diameter (mm).

4.5.1 Model Formation

The objective of the work was to come up with a better complexity definition using the eight factors mentioned earlier, which contribute to the complexity of the extrusion die. This was done by performing multiple regression analysis. First, the model for predicting the average life $\overline{T}$ was devised using the factors. After using different schemes(as briefly discussed in preceding section), to come up with a good predictive model the following was narrowed out to be the best. Since large number of factors were involved, hence to simplify, multiple linear regression was carried out using the computer package ***Statgraph Plus***. The equation of the best postulated model is:

$$Ln\overline{T} = Ln(A_o) + sLn(C.D) + tLn(X) + uLn(A) + vLn(P) +$$
$$wLn(t_{min}) + xLn(CCD) + yLn(W_p) + zLn(W/L) \qquad (4.13)$$

When the inverse logarithm was taken the equation became:

$$Predicted\ \overline{T} = \frac{A_o(C.D.)^s(X)^t(A)^u(P)^v}{(t_{min})^w(CCD)^x(W_p)^y(W/L)^z} \qquad (4.14)$$

Multiple regression model of Eq. 4.13 was fitted to the data of Table 4.3, which gave the following values of the regression coefficients

$A_o = (10)^{28.3}$

s = 2.39

t = 1.03

u = 68.19

v = 1.17

w = 1.86

x = 0.82

y = 2.61

z = 66.18

The predicted and actual values are plotted in Fig. 4.25 and a normal plot of residual values is given in Fig. 4.26. These plots verify the adequacy of the proposed models. Now to make this predictive average life model in to a die complexity factor, the model was non-dimensionalized. This non-dimensionalized version of the model can be used as an index of die complexity. The predictive average life model was made non-dimensional using the corresponding factor values for a least complex die (obtained from the extensive pool of data, shown in Table 4.3). As a result the new proposed complexity factor is:

$$Comp\ 4 = \frac{(\frac{C.D.}{C.D.^*})^s(\frac{N}{N^*})^t(\frac{A}{A^*})^u(\frac{P}{P^*})^v}{(\frac{t_{min}}{t_{min}^*})^w(\frac{CCD}{CCD^*})^x(\frac{W_p}{W_p^*})^y(\frac{W/L}{W/L^*})^z} \tag{4.15}$$

where,

$*$ represents values corresponding to minimum die complexity.

Table 4.3: Table of the factors influencing the die complexity, predicted average life $\overline{T}$ and proposed complexities of dies. [where $Y = \ln[\ln[1/[1-F]]]$, $X = \ln(t)$ and η (kg) = η/w (number of pushes): w = weight of a billet]

S. No.	Die No.	Regressed Weibull Equation	Scale Parameter kg.	Shape Parameter	Average Life kg	C.D mm	tmin mm	N	A sq-mm	CCD mm	P mm	W.P mm	W/L kg/m	Pred. T Eq. 4.14	Comp 4	Comp 5
1	H9028	Y = 1.260X-11.649	10386.2	1.26	9659.2	190	1.3	1	357	109	550	820	0.964	10557.30	0.57	0.39
2	H4525	Y = 1.054X-9.961	12694.5	1.054	12419	190.3	1.3	2.53	182	126.5	272	419.3	0.492	14799.48	0.41	0.29
3	H9049	Y = 0.752X-6.822	8727.6	0.752	10368.3	186	1	2	156	120	312	464	0.422	11806.27	0.51	0.37
4	H9046	Y = 1.488X-14.224	14196.7	1.488	12826.7	186	1	1	236	89.5	472	704	0.637	10685.72	0.56	0.50
5	H9023	Y = 1.052X-10.080	14479.2	1.052	14187.9	224	1.5	1	604	128	722	1210.4	1.631	15041.31	0.40	0.27
6	H9050	Y = 1.664X-16.374	18775.2	1.664	16775.8	188.28	1.3	1.06	327	92	434	592	0.883	18736.53	0.32	0.31
7	S9064	Y = 1.253X-12.320	18694	1.253	17396.6	186	1.3	4	97	125	131	131	0.267	17163.58	0.35	0.11
8	S9017	Y = 1.490X-14.897	21991	1.49	19866.7	186	1.3	1	319	120	489	489	0.861	25586.90	0.24	0.19
9	H9022	Y = 1.109X-11.041	21124.8	1.109	20322.1	193.6	1.3	1.2	355	93	518	793.1	0.958	15919.60	0.38	0.34
10	H9019	Y = 1.838X-18.463	23044.5	1.838	20475.3	215	1.3	1.75	315	121.8	486	698.8	0.851	22822.21	0.26	0.20
11	H1464	Y = 1.178X-11.804	22448.4	1.178	21227.4	186	1.4	2	241	118	305	453	0.65	19412.23	0.31	0.28
12	H1577	Y = 2.014X-20.362	24605.6	2.014	21802.3	186	1.3	5.5	79	130	128	173	0.213	28312.17	0.21	0.20
13	H9026	Y = 1.467X-14.827	24443.7	1.467	22131.3	215.9	1.3	2.75	201	153	310	460	0.543	21775.75	0.28	0.19
14	H1553	Y = 1.587X-16.334	29450.8	1.587	26724.4	224	1.6	2	302	135	380.5	544.4	0.815	25669.77	0.23	0.17
15	H9062	Y = 2.477X-25.813	33536.8	2.477	29750.5	221.7	1.3	4	133	150	180	270	0.359	33984.86	0.18	0.17
16	H5178	Y = 1.812X-19.100	37842.8	1.812	33638.5	224	1.3	4	178	150	272	391.6	0.481	35744.81	0.17	0.13
17	H9009	Y = 1.875X-19.827	39058	1.875	34675.7	212.6	1.3	2.7	200	142.8	390	421.1	0.54	36884.01	0.16	0.11
18	H9057	Y = 1.606X-16.978	39030	1.606	34978.7	215.3	1.3	4	132	149	198	276.6	0.356	34841.99	0.17	0.16
19	H9008	Y = 1.866X-19.773	39917.4	1.866	35441.1	215	1.3	3.5	177	149	274	385.23	0.478	30792.94	0.20	0.15
20	S9006	Y = 1.374X-14.535	39195.8	1.374	35828.9	188.3	1.35	1.06	438	110	638	638	1.183	34563.78	0.17	0.15
21	S9070	Y = 1.754X-18.610	40553.9	1.754	36112.4	186	1.35	1	433	125	620	620	1.169	29793.45	0.20	0.16
22	H9032	Y = 1.631X-17.365	41949.4	1.631	37544.7	215	1.3	2.5	224	153.3	335	461.04	0.605	26796.56	0.22	0.17
23	S1466	Y = 1.262X-13.442	42088	1.262	39116.6	210	1.4	1	536	117	742	742	1.447	46756.56	0.13	0.11
24	H9052	Y = 2.013X-21.783	49949.3	2.013	44260.1	223.1	1.3	2.3	278	174.5	344	453	0.75	43383.98	0.14	0.13
25	S1465	Y = 1.269X-13.672	47993.3	1.269	44537.8	210	1.4	1	464	117	640	640	1.252	44730.28	0.13	0.12
26	S9031	Y = 1.313X-14.292	53590.5	1.313	49383.6	190.2	1.3	4.22	110	143.3	158	158	0.297	60264.70	0.10	0.10
27	S9030	Y = 1.677X-18.358	56637.5	1.677	50577.3	186	1.3	3	130	135	195	195	0.351	43599.78	0.14	0.13
28	S1113	Y = 1.173X-12.793	54469.7	1.173	51544.7	186	1.5	6.95	43	141.5	60	60	0.116	47782.51	0.13	0.11
29	S9029	Y = 1.949X-21.827	73084.7	1.949	64804.2	186	1.3	7.04	60	142.8	100	100	0.162	55491.30	0.11	0.10

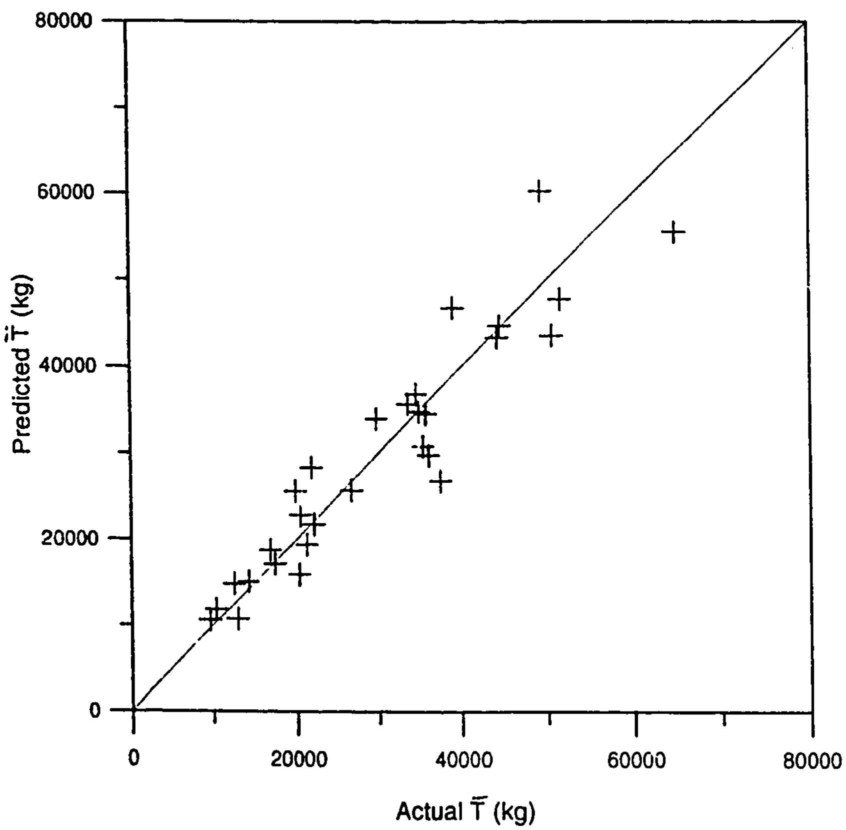


Figure 4.25: Plot showing the predicted $\overline{T}$ vs the actual $\overline{T}$ of the prediction model obtained from Eq. 4.14. [R-sq = 0.7856]

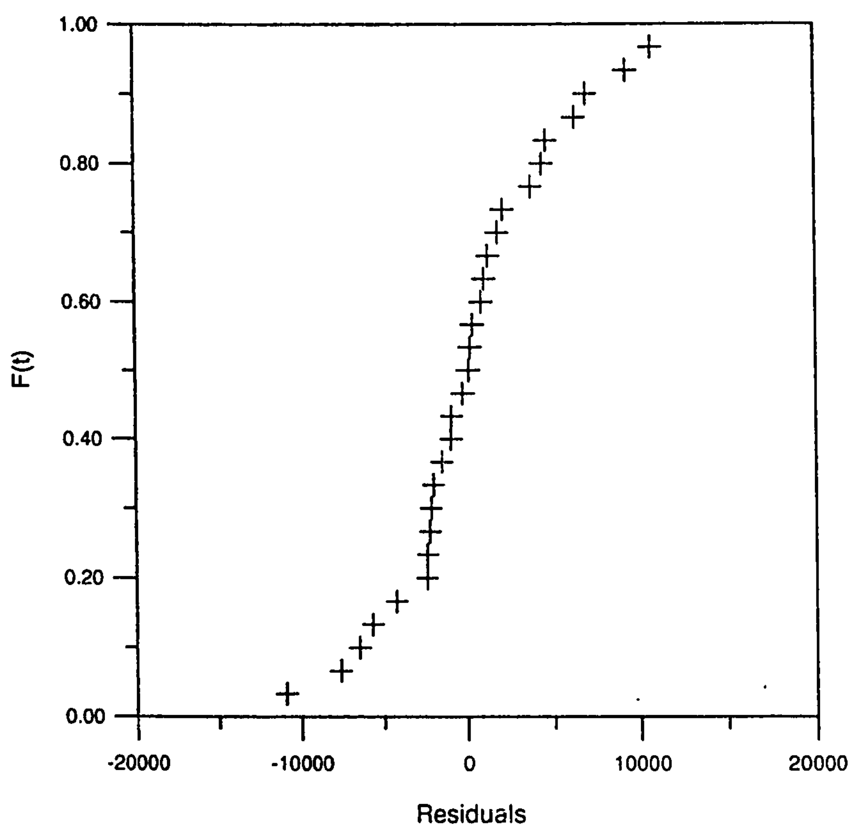


Figure 4.26: Graph showing the normal plot of residual values of the prediction model obtained from Eq. 4.14.

A further simplified version is Complexity 5, which is obtained by ignoring the weakly correlated terms in Eq. 4.14. The postulated model for the average life is:

$$Ln\overline{T} = Ln(A_m) + aLn(C.D) + bLn(A_t) + cLn(P) +$$

$$dLn(t_{min}) + eLn(CCD) + fLn(W_p) + gLn(W/L) \tag{4.16}$$

When the inverse logarithm was taken the equation became:

$$Predicted\ \ \overline{T} = \frac{A_m(C.D.)^a(A_t)^b(P)^c}{(t_{min})^d(CCD)^e(W_p)^f(W/L)^g} \tag{4.17}$$

and corresponding complexity factor(after non-dimensionalizing the above model).

Comp 5 is:

$$Comp\ \ 5 = \frac{(\frac{C.D.}{C.D.^*})^a(\frac{A_t}{A_t^*})^b(\frac{P}{P^*})^c}{(\frac{t_{min}}{t_{min}^*})^d(\frac{CCD}{CCD^*})^e(\frac{W_p}{W_p^*})^f(\frac{W/L}{W/L^*})^g} \tag{4.18}$$

where,

$A_t = (N) * (A)$ and

$A_m = (10)^{-0.8757}$

a = 1.98

b = 0.73

c = 1.85

d = 0.11

e = 0.13

f = 2.10

g = 0.03

The actual and predicted values of the model, and a plot of residual values of the model are given in Fig. 4.27 and 4.28. The plots showing the predicted average life $\overline{T}$ against the actual average life $\overline{T}$ reveal that from the two models (Eq. 4.14 and Eq. 4.17) the former (Eq. 4.14) gives a better R-sq value, hence it will be used for predicting average life $\overline{T}$. Table 4.3 provides the values of Predicted Average life $\overline{T}$ (obtained from Eq. 4.14), Complexity 4 and Complexity 5. The proposed complexities 4 and 5 and the predicted life $\overline{T}$ are plotted against the scale and shape parameters of the Weibull models to determine the relationship between them as shown in Figures. 4.29, 4.30, 4.31, 4.32, 4.33 and 4.34.

The reliability functions which are obtained through proposed complexity correlations for different profile complexities that is low(H9019; Comp. 4 = 0.26, Comp. 5 = 0.20, and Predicted Average life $\overline{T}$ = 22822.2kg), medium(H9008; Comp. 4 = 0.20, Comp. 5 = 0.15, and Predicted Average life $\overline{T}$ = 30792.9kg), and high(H9052; Comp. 4 = 0.14, Comp. 5 = 0.13, and Predicted Average life $\overline{T}$ = 43383.9kg) complexities are plotted in Fig. 4.35, 4.36, 4.37, 4.38, 4.39 and 4.40. The regression equation in Fig. 4.33 and 4.34 is used to estimate the value of η and β for a given average life. In a similar fashion the values of η and β were obtained through Comp. 4 and Comp. 5, from the regression equation in Fig. 4.29, 4.30, 4.31, and 4.32. The method for obtaining the function is the same as discussed in section 4.4.

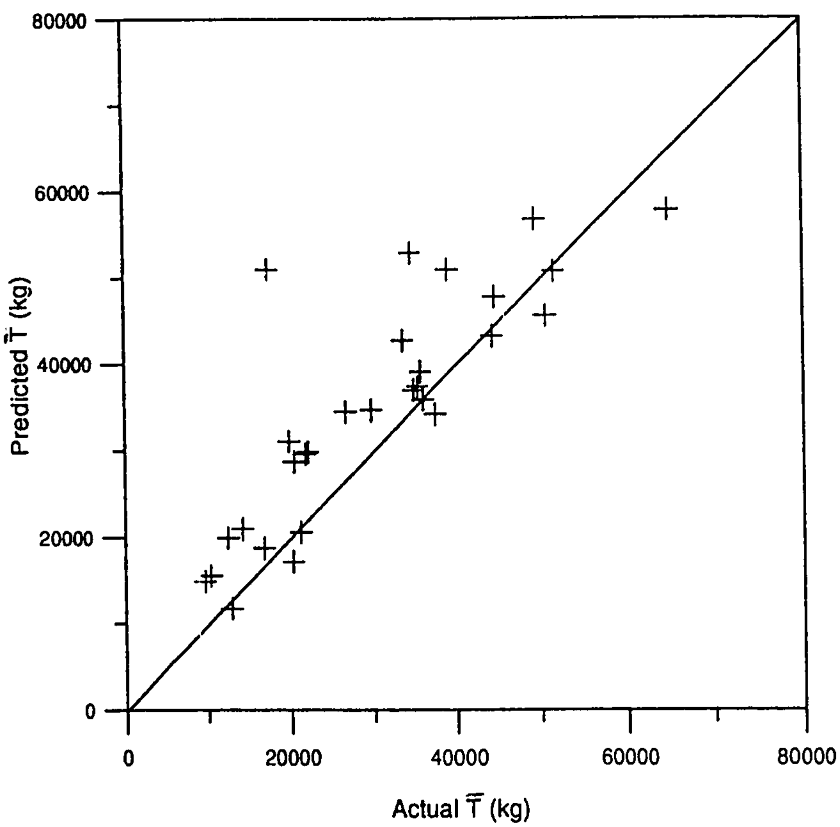


Figure 4.27: Plot showing the predicted $\overline{T}$ vs the actual $\overline{T}$ of the prediction model obtained from Eq. 4.17. [R-sq = 0.7423]

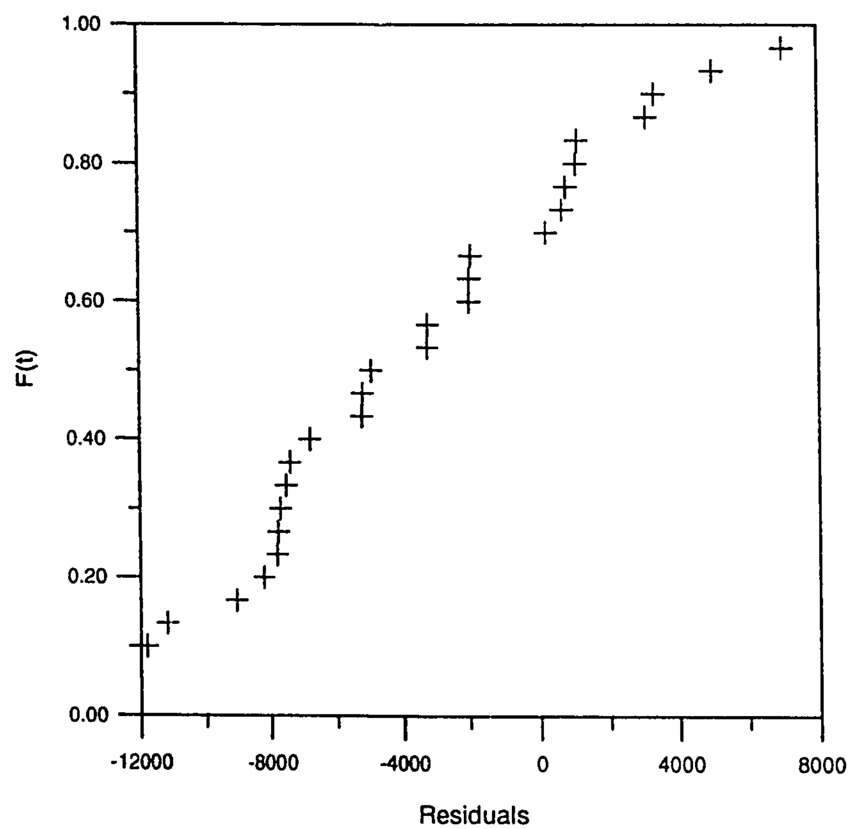


Figure 4.28: Graph showing the normal plot of residual values of the prediction model obtained from Eq. 4.17.

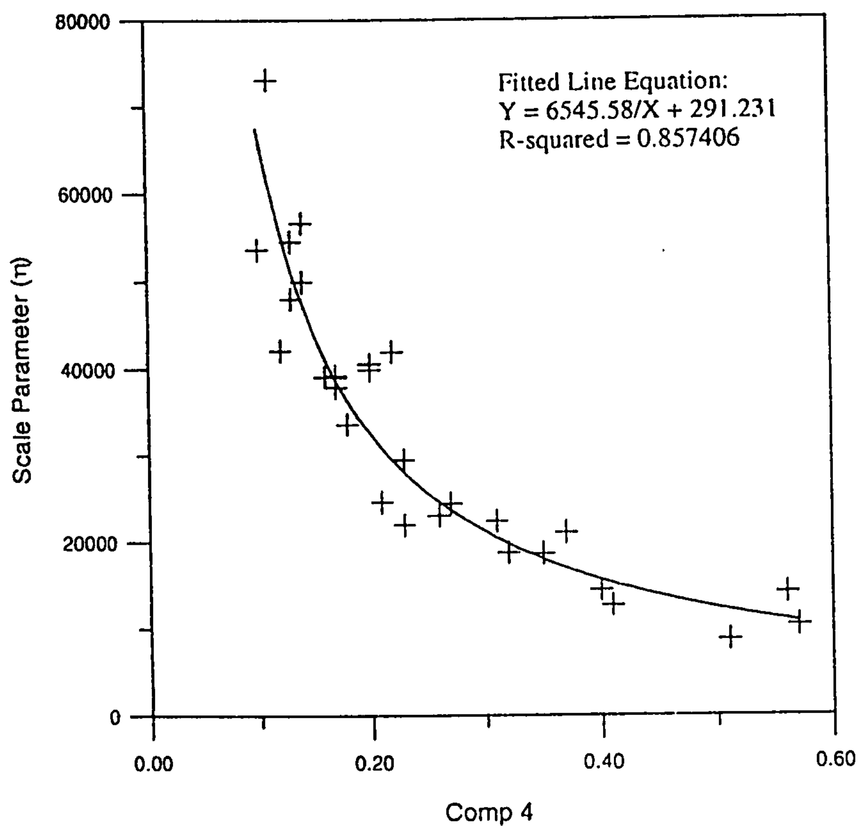


Figure 4.29: Graph evaluating the relationship between scale parameter η (obtained from weibull regression line) and the die complexity 4, η is in kg.

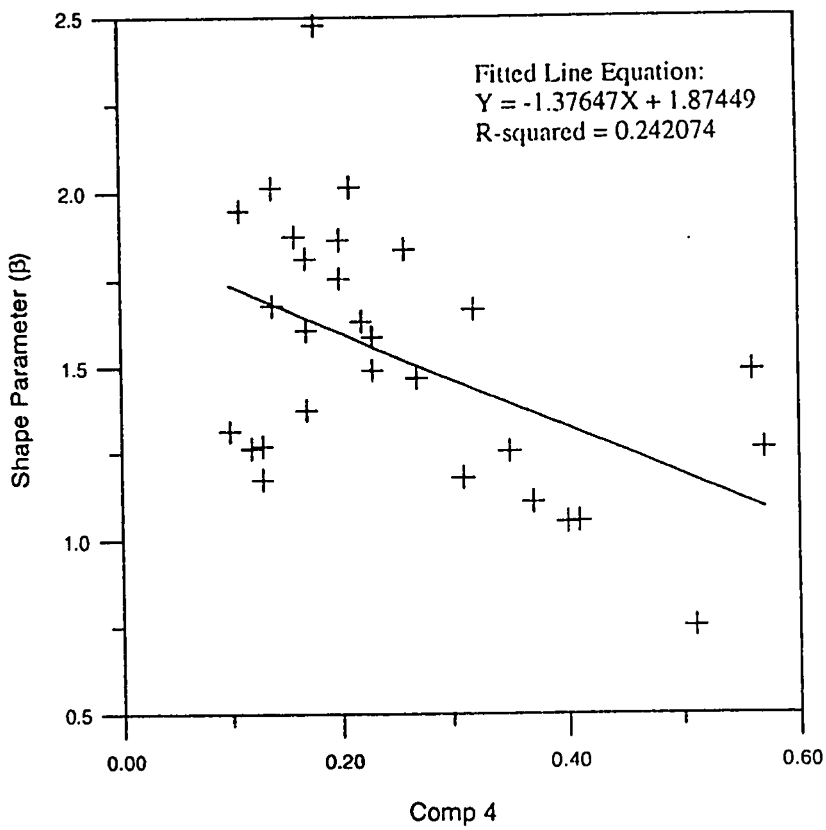


Figure 4.30: Graph evaluating the relationship between shape parameter β (obtained from weibull regression line) and the die complexity 4.

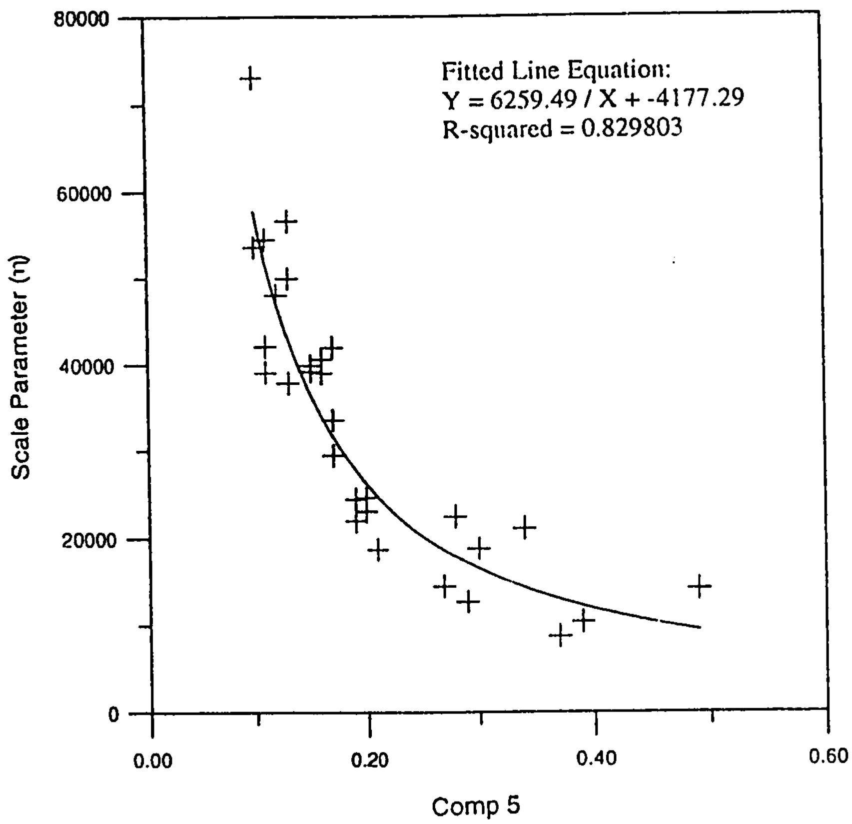


Figure 4.31: Graph evaluating the relationship between scale parameter η (obtained from weibull regression line) and the die complexity 5, η is in kg.

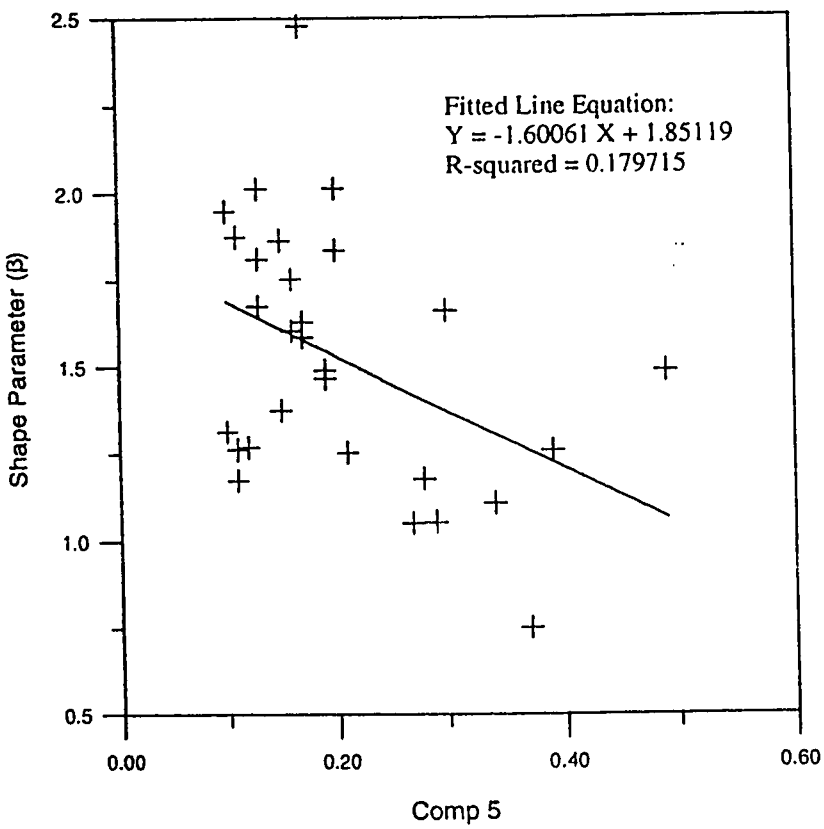


Figure 4.32: Graph evaluating the relationship between shape parameter β (obtained from weibull regression line) and the die complexity 5.

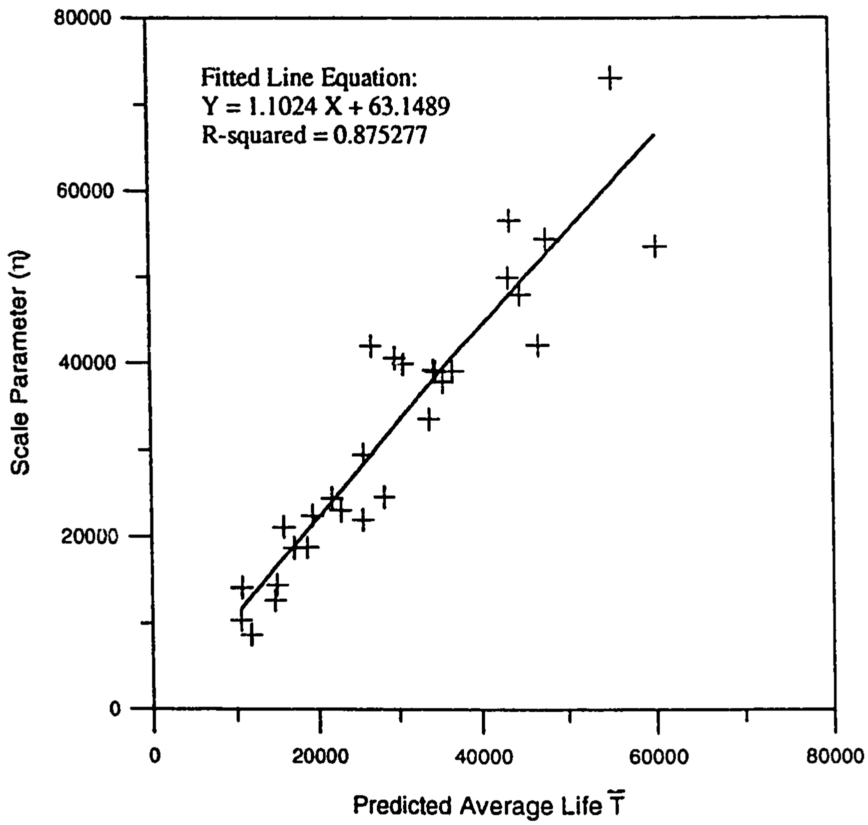


Figure 4.33: Graph evaluating the relationship between scale parameter η (obtained from weibull regression line) and the predicted average life $\overline{T}$ (obtained from Eq. 4.14), η is in kg.

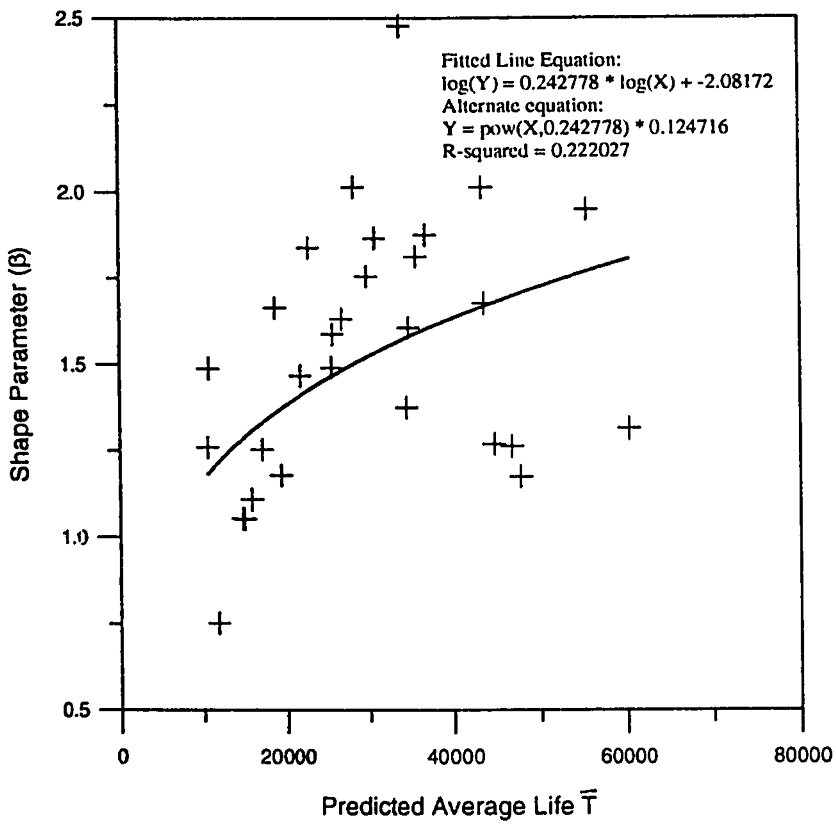


Figure 4.34: Graph evaluating the relationship between shape parameter β (obtained from weibull regression line) and the predicted average life $\overline{T}$ (obtained from Eq. 4.14).

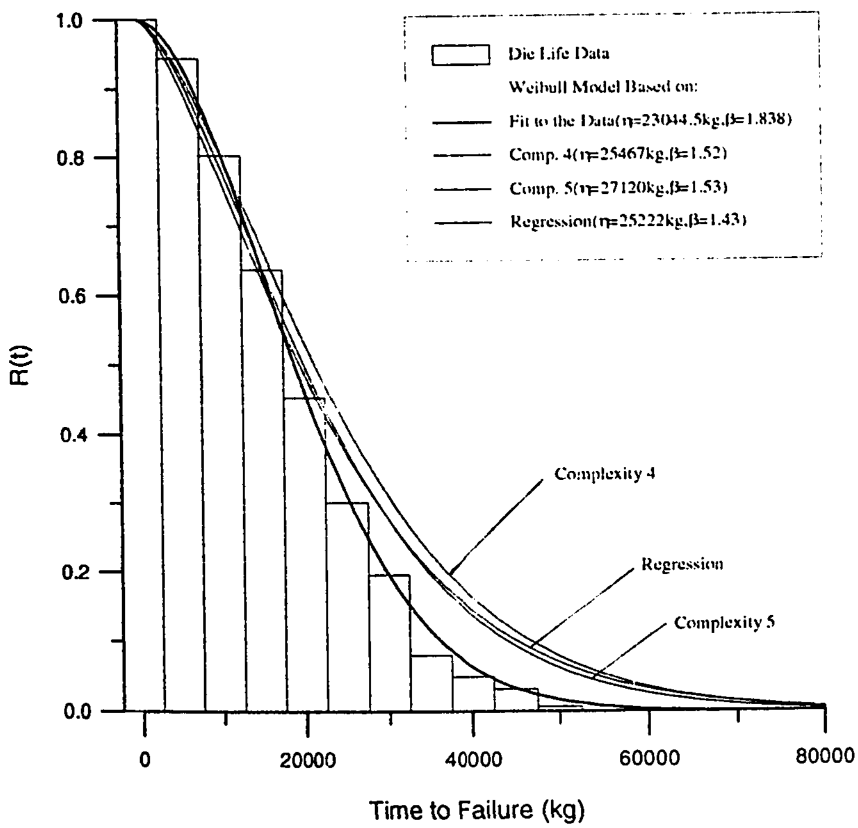


Figure 4.35: Reliability comparison obtained through different proposed complexity definitions and by direct regression (Die No. H9019).

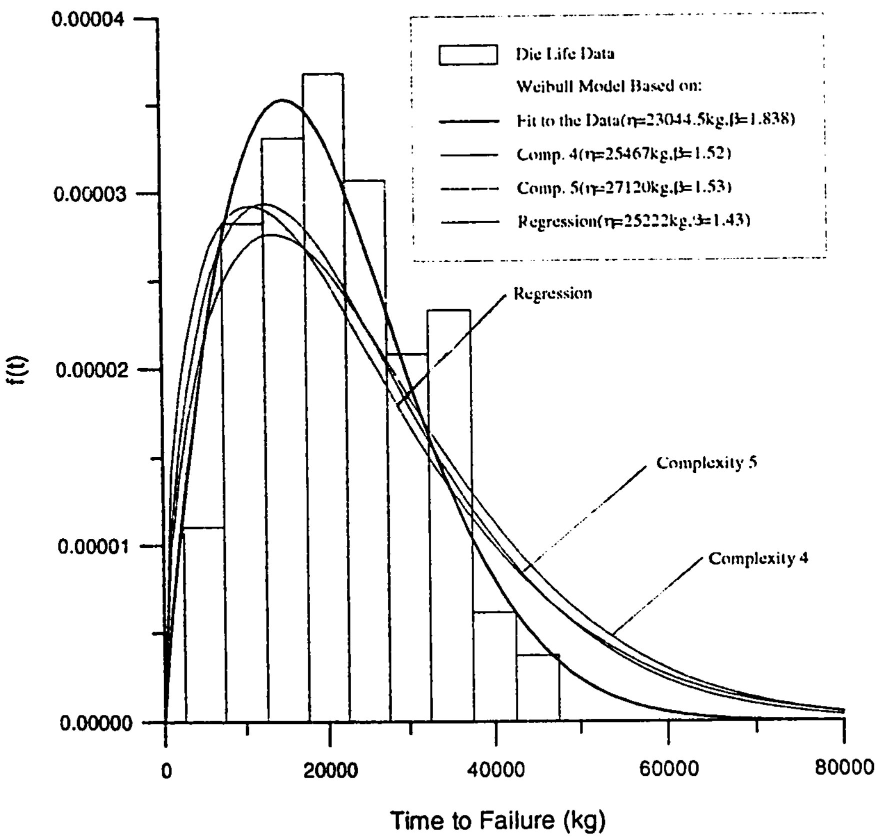


Figure 4.36: Frequency distribution comparison obtained through different proposed complexity definitions and by direct regression (Die No. H9019).

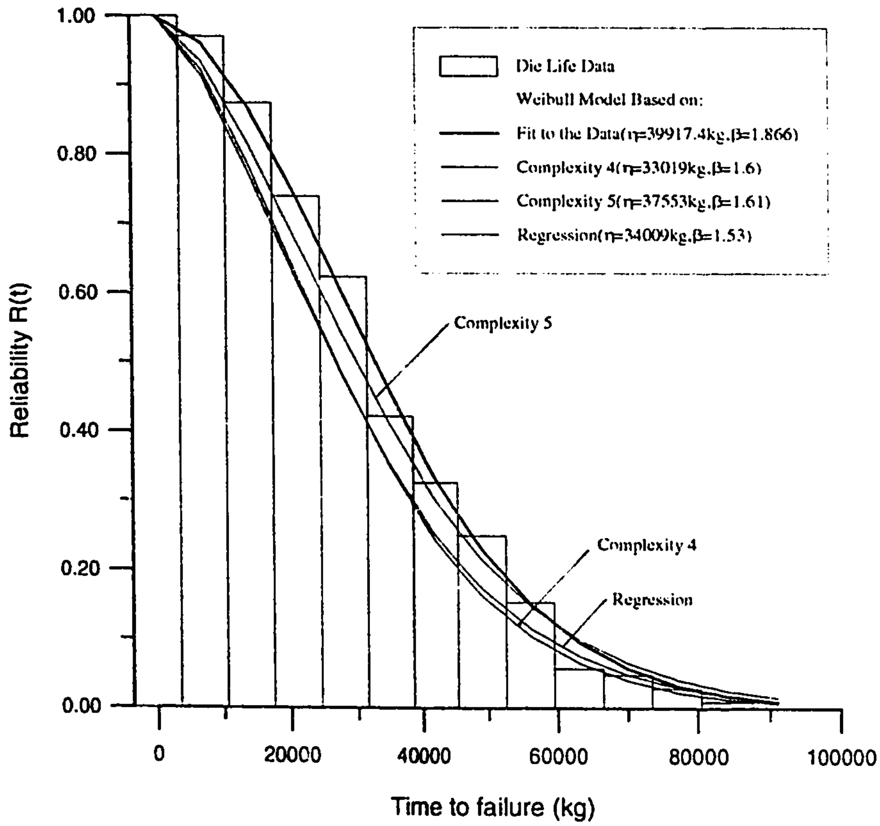


Figure 4.37: Reliability comparison obtained through different proposed complexity definitions and by direct regression (Die No. H9008).

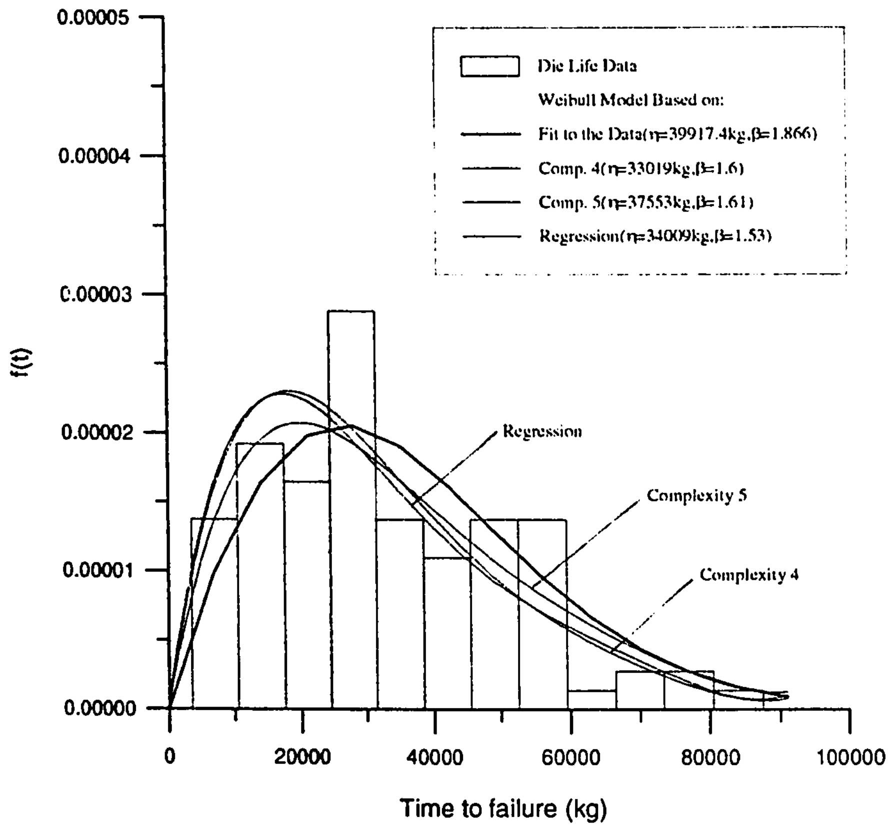


Figure 4.38: Frequency distribution comparison obtained through different proposed complexity definitions and by direct regression (Die No. H9008).

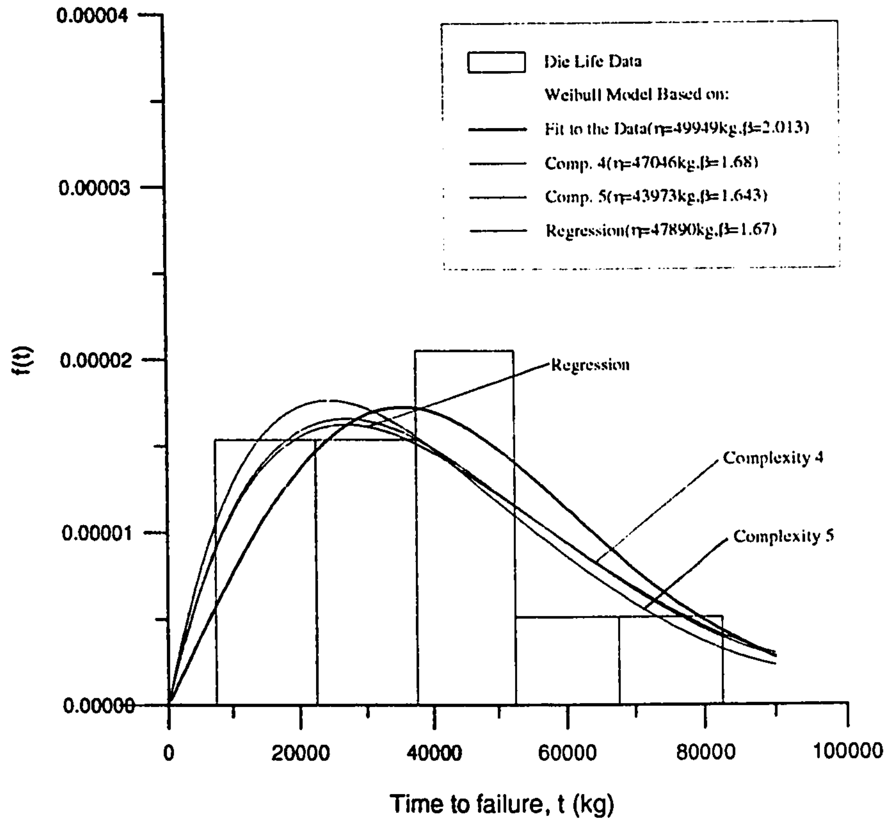


Figure 4.39: Frequency distribution comparison obtained through different proposed complexity definitions and by direct regression (Die No. H9052).

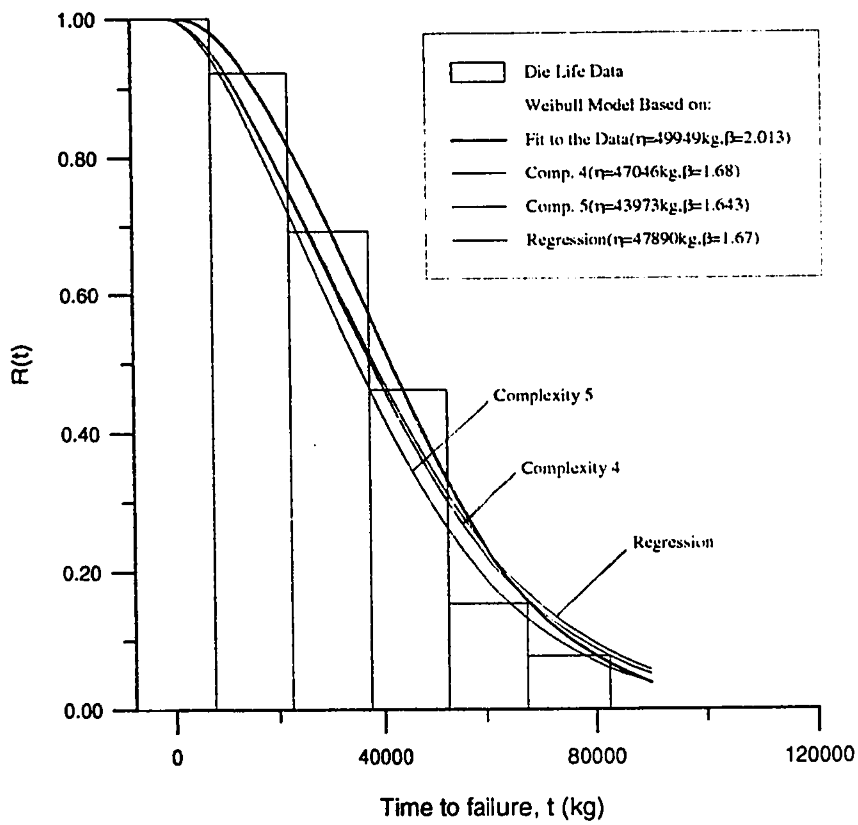


Figure 4.40: Reliability comparison obtained through different proposed complexity definitions and by direct regression (Die No. H9052).

The importance of obtaining the life of an extrusion die just by calculating the profile complexity is novel. A process engineer can now estimate the number of dies required for a typical extrusion job just by evaluating the complexity, hence reducing unnecessary overheads and delays. From the comparison of die life functions for extrusion die H9019, H9008 and H9052, it is clear that the proposed complexity 5. is the most appropriate and comprehensive complexity definition. There is a close agreement between the model, data and complexity curves. The complexity definitions existing in the literature do not give good agreement in terms of predicting the reliability of different dies, as can be seen in Figures. 4.11, 4.12, 4.13, 4.14, 4.15 and 4.16. It is observed that the reliability predicted through literature complexity definitions does give acceptable results occasionally but not always, hence the results are not dependable. It is also clear from the figures that the reliability predicted through the direct regression method is also closest to the industrial data, which is expected.

Chapter 5

Prediction of Die Reliability by Simulation, using Die Damage Models

In the previous chapter a statistical analysis of the extrusion die life data was presented, and distributions were fitted to the time to failure data due to all three major modes of die failure. The parameters of these models were correlated to various process and die design parameters, and a regression model was proposed to predict the average life. Alternatively die life reliability could be determined in-terms of a comprehensive die characterization through its complexity factor. These approaches are specific to a given plant and environment. In this chapter a more generic approach which will be based upon die damage models will be proposed.

Which will be independent of a plant and its working environment.

In the analysed data, around 40% of all die failures were found to be caused by crack propagation which resulted in fracture and ultimately to die failure, the other major cause of failure was wear or over weight, while mandrel deflection is also a cause of die scrapage in some cases (Table 3.1).

Owing to the complexity of the different wear and fracture mechanisms the physically meaningful concept of fatigue under cyclic load [35] and wear failure due abrasive action has been used under probabilistic framework to simulate the life distribution of the extrusion dies corresponding to each mode of failure.

In the models. an attempt has been made to correlate the stochastic nature of the fatigue and wear properties of the die material to its life. *Monte Carlo Simulation* has been used to predict the life distribution of the die for a given set of manufacturing conditions and the mechanical properties of the die. Further. the die life reliability and other statistical characteristics such as mean life and variance of life are estimated from the simulated data and the plots representing the different statistical functions are compared with the model and industrial data functions.

For the simulation and model formation we will focus on the major cause of die failure which are fracture and wear. here we will ignore the deflection of the mandrel. It is assumed that the die is primarily subjected to simultaneous wear and fatigue damage processes and the die life is limited by either one of the two(i.e. which ever incur the critical level of damage first).

The life criteria used in the simulation model are;

1- The fracture crack reaching the critical values (using the fracture mechanics fatigue life model).

2- Wear reaching to a critical value (using the wear theory based model).

Then as a comprehensive model which incorporates both the fracture and wear mechanism. competitive risk simulation model is proposed for the extrusion die life prediction.

5.1 Skeleton of the Methodology

The simulation of a die life for practical implementation in manufacturing environment involves the following steps:

- Developing the die life model applying the wear or fracture mechanics approach to fatigue analysis. $X_f = g\ (X_1, X_2, \ldots, X_n; Y_1, Y_2, \ldots, Y_n)$

- Collection of available mechanical properties data of the materials used in the model and their distribution characteristics. $X_1, X_2, \ldots, X_n$

- Collection of parametric constants of the fracture mechanics based model, and parameters of the wear model, including the characteristics of the distributed quantities $Y_1, Y_2, \ldots, Y_n$

- Calculating the die life N_f values using a generated set of random input quantities $x_1, x_2, ..., x_n; y_1, y_2, ..., y_n$ in a successive repetitive manner and establishing its statistical distribution for further use in reliability estimation for each failure model using the appropriate model.

- Comparison of empirically fitted die life distribution with the appropriate die times to failure data for each mode of failure.

- Finally developing reliability model for die life under competing modes of failure, and comparison of the result with the corresponding model(s) of Table 4.2.

5.2 Simulating Die Life Subjected to Fatigue Crack Growth: Fracture Mechanics Based Approach

Through the years, fracture mechanics has developed into a useful tool in the design of crack-tolerant structures, in fracture control and in life assessment of machine elements, it also has contribution in failure analysis [36]. Fracture mechanics can provide helpful quantitative information on the circumstances that lead to failure, and it can be used to substantiate preventive measures to avoid the recurrence of failure in similar components. Fracture mechanics approach will be used to construct a die life model for extrusion dies. It is observed that the fracture or some level of micro chipping (which is reflected in bad quality produced with scratches for example) of the die occurs at the stresses much below the yield strength of the die material under cyclic stress condition. Several aspects of the operation and nature of these dies suggest a potential for failure resulting from the growth of cracks on the bearing surface. First, during normal operations, the dies are subjected to large, repeated loads. Second, the cavities in both dies create regions of high stress concentration specially at race ways and at intricate braces, where cracks can initiate and grow resulting in catastrophic failure. Third, in order to produce profiles of well controlled shape and dimensions, the dies are made of high strength, hardened material for e.g.(H-13), and during hardening operation usually initial small cracks are developed which under cyclic loading will propagate to a critical value and will make the die scrap. In order to provide a general format for the fracture analysis of these dies, the following information can be identified as essential basis for the model formation.

1. Evidence of crack initiation and assessment of the shape and size of the initial flaws(i.e. cracks)

2. Material properties for fracture and fatigue

3. Stress analysis and parameters of Paris equation

4. Failure hypothesis

5.2.1 Model Formulation

The basic purpose of this research is to establish the effect of stochastic variability of different factors such as. mechanical properties, part geometry and stresses involved, etc., on the actual die life distribution in an extrusion process. The physical model introduced is an expression derived to correlate the fatigue and fracture properties of the die material to the life of the die. expressed in number of cycles of load applied before failure. The life of an extrusion die can either be expressed in the weight of material (kg) extruded or for fatigue analysis in the number of billets extruded because each billet being extruded corresponds to the stress cycle which will be further discussed in detail.

5.2.2 Forces Acting on an Extrusion Die

The direct extrusion process and the forces that act on the die surface during the extrusion of a billet have been extensively investigated analytically [37]. The friction involved between the billet and the container surface has been taken into consideration. The dead zone at the end of the extrusion chamber has been approximated as a surface inclined at 45^o angle, with the billet surface. It is also assumed that the material deforms in a simple uniform manner as it goes from the larger diameter d_o to smaller d_i as shown in Fig. 5.1. The force calculations are performed in an order of steps as mentioned below [38].

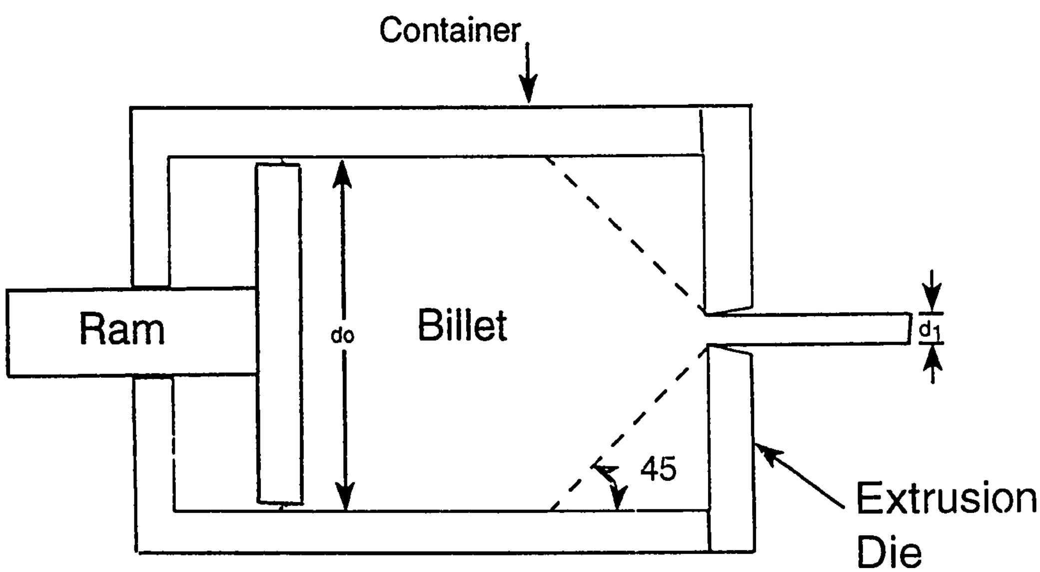


Figure 5.1: Idealized extrusion process

Step 1: The dimensions considered are the cross-sectional area of the billet A_o and profile area A_i, with diameters d_o and d_i. When the profile is a non circular, the diameter of the profile d_i is evaluated by equating to an equivalent circular area.

Step 2: The true strain is calculated as the logarithmic of R_e i.e.,

$$\epsilon = \ln R_e = \ln \frac{A_o}{A_i} \tag{5.1}$$

Step 3: In cold working, the strain hardening of the work piece material during its passage through the die and the mean flow stress σ_{fm} can be obtained as

$$\sigma_{fm} = \frac{K}{\epsilon}\left\{\frac{\epsilon^{n+1}}{n+1}\right\} \tag{5.2}$$

Where κ is the strength coefficient in cold working and n is the strain hardening exponent. But for our case of hot extrusion the mean flow stress is given as a power function of the strain rate $\dot{\epsilon}$ and is estimated as [38].

$$\sigma_{fm} = A(\bar{\dot{\epsilon}})^{p} \tag{5.3}$$

where A is the strength coefficient in hot working and p is the strain rate sensitivity exponent. And the strain rate itself is a function of instantaneous deformation velocity and the instantaneous length of workpiece and is expressed as

$$\dot{\epsilon} = \frac{V}{h} \tag{5.4}$$

where as the mean strain rate, $\bar{\dot{\epsilon}}$ is expressed as

$$\bar{\dot{\epsilon}} = \frac{6Vd_o^2 tan\alpha}{d_o^3 - d_i^3}\epsilon \tag{5.5}$$

here α is the semi die angle. in this work it is assumed to be 45^o

Step 4: Deformation being an inhomogenous process, the extrusion pressure p_e is approximately calculated to be

$$p_e = \sigma_{fm} Q_e = \sigma_{fm}(0.8 + 1.2\epsilon) \tag{5.6}$$

Step 5: The extrusion force F_e acting on the billet is estimated as

$$F_e = p_e.A_o \tag{5.7}$$

Step 6: In direct extrusion, the billet is pushed forward against the frictional resistance developed on the container wall. Correspondingly, the extrusion pressure is higher at the beginning of the stroke when a long length rubs against the container wall. Also, at high extrusion ratios interface pressures can be very high and the use of a coefficient of friction value may not be accurate. Therefore, the shear strength of the interface τ_i and the pressure due to friction is added to the pressure in Eq. 5.6 and the total pressure is given by the expression

$$p_t = p_e + \frac{4\tau_i l}{d_o} \tag{5.8}$$

where l is the length of the billet at the point in the stroke considered and measured from the end of the stroke. The value of τ_i is generally assumed to be equal to [39].

$$\tau_i = 0.5\sigma_{fm} \tag{5.9}$$

The pressure p_t at the center of the die opening causes tangential and radial stresses on the surface. These stresses can be considered to be similar to the stresses encountered in case of a thick cylinder subjected to internal fluid pressure. As a first approximation we assume the case to be similar to the case of thick wall cylinder and use the *Lame's* theory to approximate the stresses acting on the die due to the extrusion pressure acting internally.

According to *Lame's* theory for thick cylinders, the tangential stress at a radius(r) from the center of the die opening is given as

$$\sigma_t = p_t \frac{r_i^2}{r_o^2 - r_i^2}\left\{1 + \frac{r_o^2}{r^2}\right\} \tag{5.10}$$

where r_i is the radius of the die opening, r_o is the outer radius of the die and r is any radius from the center of the die opening. p_l is the pressure exerted by the metal being extruded on the die. Similarly the radial stress acting on the die is given as

$$\sigma_r = p_l \frac{r_i^2}{r_o^2 - r_i^2}\left\{1 - \frac{r_o^2}{r^2}\right\} \tag{5.11}$$

But the radial stress being compressive in nature is neglected, because the growth of the crack is stopped due to the compressive stress. The maximum tangential stress is estimated by the following expression [40].

$$\sigma_{max} = p_l \frac{r_o^2 + r_i^2}{r_o^2 - r_i^2} \tag{5.12}$$

where r = r_i.

The value of the maximum tangential stress is used in the expression for the cycles to failure to estimate the life of the die.

5.2.3 Life Assessment through Fatigue Crack Growth

A die can be approximated as a thin plate with a small elliptical crack of length a, as shown in Fig. 5.2. The die is considered a thin plate because of the plane strain condition (if plane stress rather than plane strain conditions prevail than the die will be considered a thick plate, some modifications will be needed in the equations).

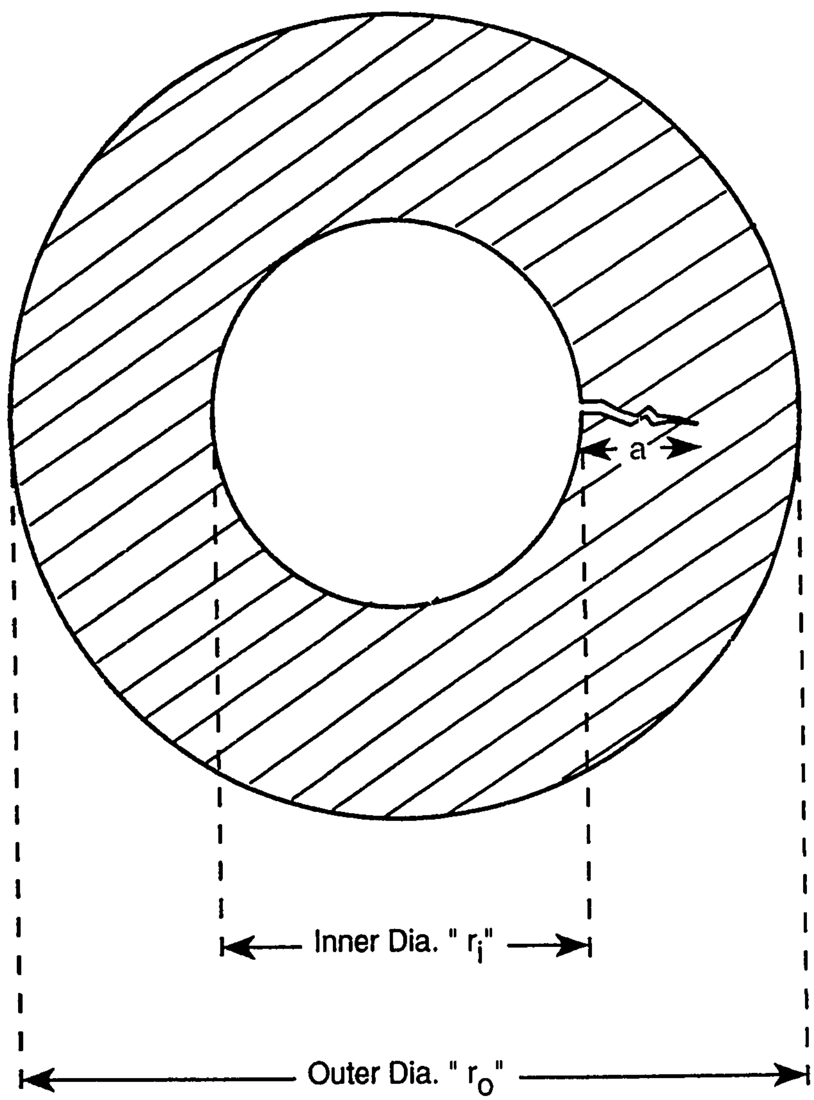


Figure 5.2: Die with an edge crack.

The nominal stress which acts at the crack tip is estimated on the basis of the material properties and the direction of the stress. In general, we may consider this nominal stress as σ. Now the local stress that acts at the crack tip is a measure of the product of the nominal stress σ and the square root of the half flaw length a.

The severity of maximum stress acting at a critical point like a bend, groove or a notch is measured by the stress intensity factor

$$K = \alpha\sigma\sqrt{\pi a} \tag{5.13}$$

and a critical value of this is called the fracture toughness(Fig. 5.4) which is also considered as the mechanical property of the material K_{1c}, and a component fails when $K \geq K_{1c}$. In Fig. 5.4 the horizontal axis represents the stress intensity range ΔK, given by:

$$\Delta K = K_{max} - K_{min} = \alpha\sqrt{\pi a}(\sigma_{max} - \sigma_{min}) \tag{5.14}$$

where, α is a factor depending upon the crack geometry.

Fracture toughness K_{1c} depends upon the mode of failure, in this work the crack opening **mode I**, with a plain strain condition is considered to be a better approximation for the case of a die failure. Since the radial stress acting on the die can be neglected due to its compressive nature, only the tangential stress is considered which is tensile in nature. Since the thickness of the die in the radial direction is more, the case can well be approximated by plain strain condition. The fracture toughness is a basic material property and is dependent upon the metallurgical variables as well as heat treatment, texture, melting practice, impurities and inclusions. The fracture toughness value K_{1c} is readily available in most of the fatigue design books for the different materials, however, there is a scarcity of data on H-13 tool steel especially at elevated die working temperature(500°C). Therefore, experimental evaluation of K_{1c} values was carried out as discussed in the following section.

5.2.4 Experimental Evaluation of Fracture Toughness

The incipience of cracks due to tangential stresses on the die bearing surface and the growth of the crack are the crucial factors determining the life of a die. The crack growth rate in a material is dependent on its fracture toughness K_{1c} [Mode I]. Hence to evaluate the true working fracture toughness of the die material under the working temperature, Charpy test was carried out on a number of test specimens. The specimens of H-13 tool steel were provided by requesting the die manufacturers in Germany and Switzerland, while the surface carbo-nitriding was done in ALUPCO facility.

The Charpy V-notch test is commonly used to evaluate the dynamic fracture toughness of steels. This is done by correlating actual fracture toughness data with the impact energy absorbed during fracture. Different correlations exist for various classes of steels, for H-13 tool steel (ultrahigh-strength steel) the correlation given by Ault et al. [41] is used.

$$\left\{\frac{K_{1c}}{\sigma_y}\right\}^2 = 1.37\left\{\frac{CVN}{\sigma_y}\right\} - 0.045 \tag{5.15}$$

where,

K_{1c} is the fracture toughness in MPa$\sqrt{m}$

σ_y is the yield strength of H-13 steel in pascal (Pa)

CVN is the impact energy in joule (J)

Table 5.1 shows the impact energy values in joules. their corresponding empirical cumulative frequencies and the fracture toughness obtained through Eq. 5.15. In Fig. 5.3 the standard normal distribution, Φ^{-1} (F), is plotted on the vertical axis and fracture toughness is plotted on the horizontal axis. If the failure data is normally distributed (as evident from the graph), the line will be straight. Since F(μ) = 0.5 for normal distribution. the mean, μ, is determined as the value for which F = 0.5 . Similarly, since F($\mu + \sigma$) = 0.84, the value of σ is just the horizontal distance between the points F = 0.84 and F = 0.5 .

The results of the experiment at elevated(500°C) and room temperature of both the surface hardened and non-surface hardened specimens are tabulated in Table 5.2.

Table 5.1: Tabulated results of Charpy test Analysis, to evaluate the Fracture toughness of H-13 tool steel.

Conditions	CVN (J)	i=1/N+1	K_{1c} (MPa$\sqrt{m}$)
Room Temp. Non-Hardened	10.0	0.25	21.9
	11.5	0.5	28.2
	14.5	0.75	37.9
Elevated Temp. Non-Hardened (500°C)	40	0.25	78.1
	36	0.5	67.7
	34	0.75	64.3
Elevated Temp. Hardened (500°C)	38.0	0.2	68.9
	33	0.4	63.2
	31.5	0.6	61.3
	30	0.8	59.5

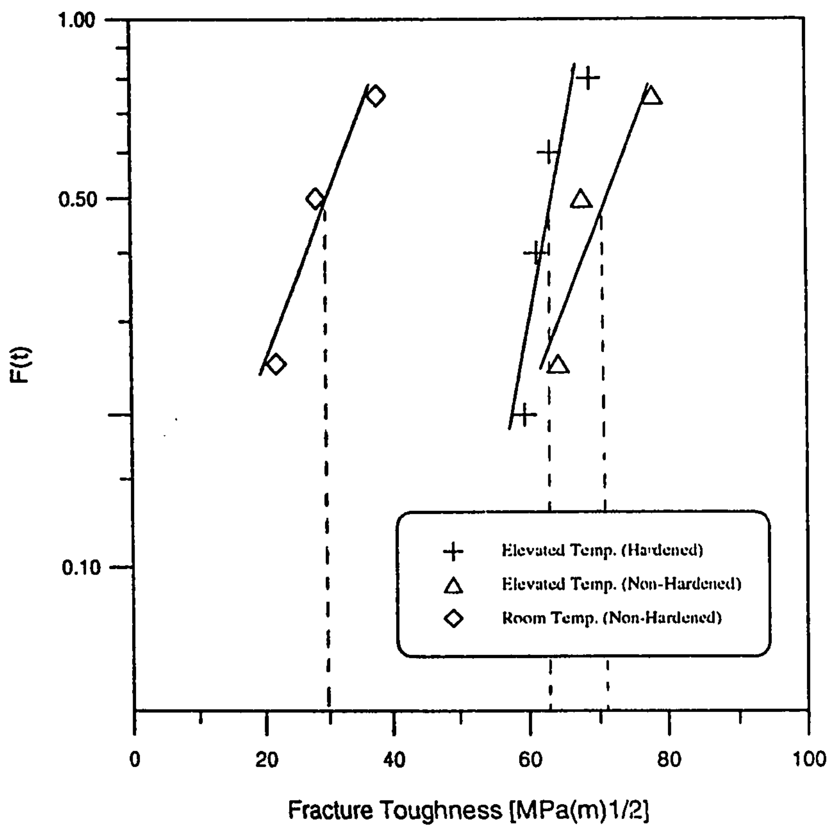


Figure 5.3: Normal Probability Plotting for the Fracture toughness of H-13 tool steel at room temperature and elevated temperature(500°C), for hardened and non-hardened tool steels.

Table 5.2: Fracture toughness mean and standard deviation, evaluated through Normal probability plotting.

Conditions	Mean (μ)	St. Deviation (σ)	% Deviation = Std./Mean
Room Temp. Non-Hardened	30	12	40%
Elevated Temp. Non-Hardened (500°C)	71	11	15%
Elevated Temp. Hardened (500°C)	63.5	5	8%

5.2.5 Hardening and Tempering to Improve the Wear Resistance, and Introduction of Cracks

Hot work tool steels are amenable to nitriding, which produces a hard, wear resistant surface layer. Nitriding of extrusion dies not only improves wear resistance but also reduces friction. In the context of wear resistance, the temper resistance, hot strength and hot hardness of the steel are all important. In the region of contact between die and extruded metal. considerable deformational and frictional heat is developed and high temperatures are experienced. Appreciable wear will thus result should the temperature become so high that the surface of the die steel in the land region softens extensively. In case of a nitrided die, the underlying steel cannot, under such circumstances, give proper support to the nitrided layer which will wear more rapidly than usual. The nitrided layer is usually upto 0.1mm (0.004in) thick and has a surface hardness exceeding 1000 HV. In the process of nitriding minute cracks are often generated in the nitrided layer. In literature a typical size of such cracks is shown to be 0.00005m for H-13 tool steels [42].

5.2.6 Intermittent/Cyclic Loading

Considering the nature of the dynamic loading on the die surface the stress cycle can be approximated to be a repeated stress cycle, with the minimum of the stress being zero. The mean stress that acts on the die material can be estimated as

$$\sigma_m = \frac{\sigma_{max} - \sigma_{min}}{2} \tag{5.16}$$

Since the minimum stress is zero when the ram is withdrawn from the work material, the mean stress is given as

$$\sigma_m = \frac{\sigma_{max}}{2} \tag{5.17}$$

In general, it is helpful to think of the ultimate failure in terms of three main stages of crack growth

1) Crack initiation.

2) Slow, stable crack propagation.

3) Rapid, catastrophic crack propagation.

Fig. 5.4 represents the rate of crack growth with reference to the cyclic stress intensity range ΔK, which is defined as shown in Eq. 5.14. It can be seen from the figure that in general, the fatigue crack propagation consists of three regions . Region I indicates a threshold stress intensity value K_{th}, below which the crack does not propagate. Region II, indicates a linear relationship between the crack growth rate and ΔK and this can be represented by a relation called the *Paris* equation

$$\frac{da}{dN} = C(\Delta K)^m \tag{5.18}$$

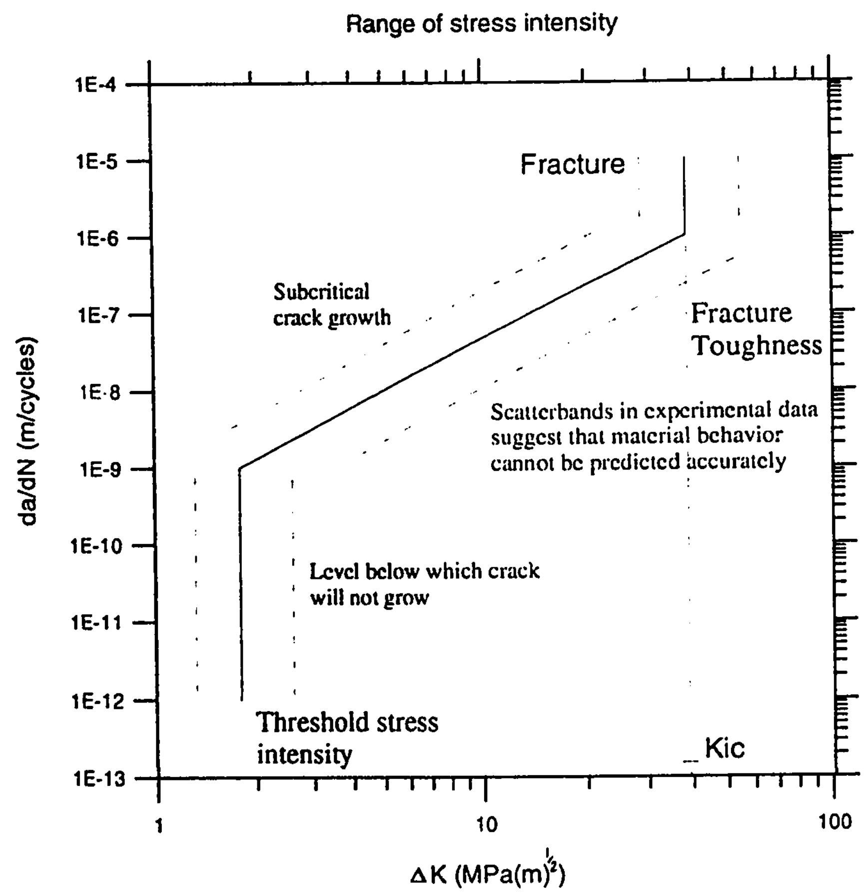


Figure 5.4: Diagram showing the relationship of crack growth with the number of cycles.

where m is the slope of the curve and C is the value found by extending the line to $\Delta K = 1$ MPa$\sqrt{\mathrm{m}}$. The material parameter C and m are treated as random variables in this application. Region III is the accelerated crack growth region where the maximum value of the stress intensity K_{max} exceeds the fracture toughness of the material $[K_{max} > K_c]$.

Since the fatigue failure in this study occurs due to reversed stress cycle conditions, with $\sigma_{min} = 0$, the stress ratio is (R=0) i.e., the fatigue crack growth data will be determined under conditions of pulsating tension. The compression loading factor on the die will not be considered because under compression the crack is closed and the stress intensity factor becomes zero.

5.2.7 Expression for Cycles to Failure

Now, in order to estimate the cycles to failure of the die material, a model which relates the fracture mechanics approach to fatigue is formulated [43].

From Eq. 5.14

$$\Delta K = \alpha \Delta\sigma \sqrt{\pi a} \tag{5.19}$$

where,

$$\sigma = \sigma_r = \Delta\sigma = \sigma_{max} - \sigma_{min} \tag{5.20}$$

since minimum stress is zero, hence

$$\sigma_r = \sigma_{max} \tag{5.21}$$

Eq.(5.18) $\Rightarrow$

$$\frac{da}{dN} = C(\Delta K)^m$$

$$\frac{da}{dN} = C(\alpha\sigma_{max}\sqrt{\pi a})^m \tag{5.22}$$

$$\frac{da}{dN} = C\alpha^m\sigma_{max}{}^m(\pi a)^{\frac{m}{2}} \tag{5.23}$$

$$\Rightarrow dN = \frac{da}{C\alpha^m\sigma_{max}{}^m(\pi a)^{\frac{m}{2}}} \tag{5.24}$$

Integrating Eq.(5.24) with the limits of crack length initially a_i and finally at failure given by a_f we have,

$$N_f = \int_{N=0}^{N_f} dN \tag{5.25}$$

$$N_f = \frac{1}{C\alpha^m\sigma_{max}{}^m\pi^{\frac{m}{2}}}\int_{a_i}^{a_f^*}\frac{da}{a^{\frac{m}{2}}} \tag{5.26}$$

where,

$$a_f^* = (a_f) * (R) \tag{5.27}$$

here, R is a constant.

and

$$a_f = \frac{1}{\pi}\left\{\frac{K_{1c}}{\sigma_{max}\alpha}\right\} \tag{5.28}$$

By using Eq. 5.26 we can get the life of a particular die in number of cycles or billets extruded. The die life will be given in number of pushes or interms of number of billets extruded. Die life in the total weight of metal extruded (kg), can then be evaluated by multiplying the die life by the weight of a single billet.

Final crack length a_f^* is the limiting value of crack length which can be tolerated. The accurate assessment of a_f^* is essential for having a reliable prediction. The hypothesis regarding a_f^* is discussed in the next section.

5.2.8 Failure Hypothesis

The load history and physical examination of the failed die indicated the occurrence of a brittle fracture mostly with no significant plastic deformation during fracture of the bearing surface of the die. Plastic deformation was observed in the mandrel which deflected plastically to such an extent that large cracks are usually visible on the mandrel surface. The failure surface indicated that fracture started from a very small defect at the root of the die cavity. This defect, when the die was intermittently fully loaded, characterized catastrophic growth leading to immediate die fracture. The presence of the crack on the bearing surface is evident due to the micro defects such as micro cracks, voids, interstitial and foreign inclusions in the material. Micro cracks are commonly present in any metallic structure as a result of inherent manufacturing defects during casting, thermal expansion and contraction, and specially due to quenching, etc. The critical aspect of these micro cracks is that some of them can propagate to a complete fracture on the application of stress.

The final crack size which is a detrimental parameter in evaluating the life of the die needs some explanation. It is important to note that the die failure is considered not only when fracture occurs but also when a crack on the die opens wide enough to cause die lines or other defects on the surface of the die. Hence, after observing the crack size on a number of dies which were declared useless or failed, a factor of $R = 1/2$ was used between the crack length a_f given by Eq. 5.28 and the limiting crack size a_f^* given by Eq. 5.27 determining the die life, which is smaller than a_f. The value of a_f^* for representative dies ranges from 5 to 8 mm. Fig. 5.5 shows the relationship between crack length a_f and the maximum nominal stress σ_{max}.

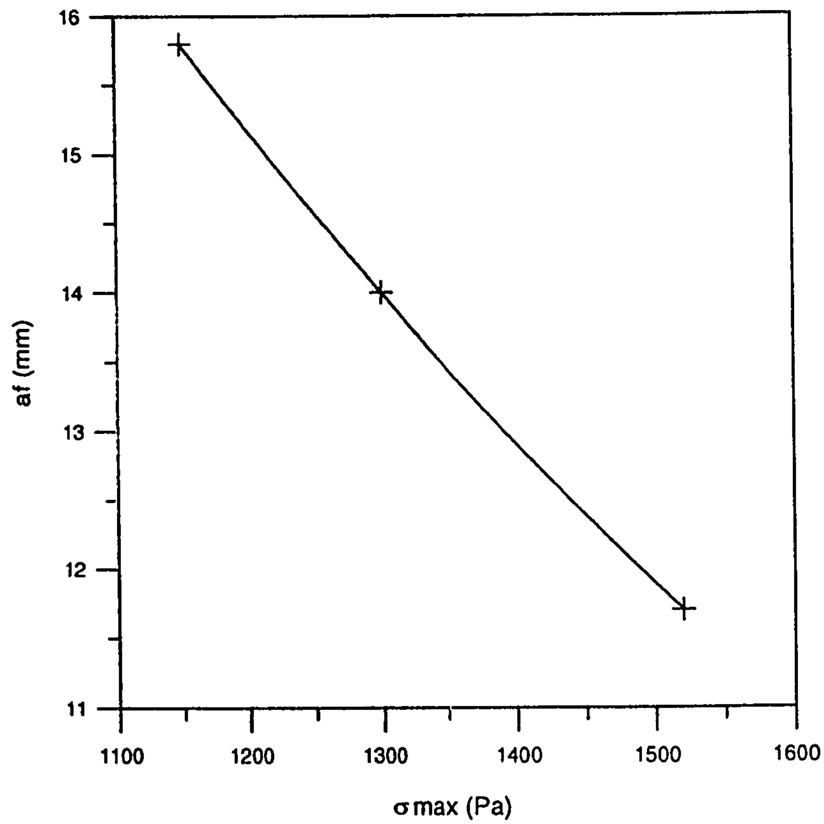


Figure 5.5: Graph showing the relationship between crack length $a_f = (a_f^*) * (R)$ and the maximum nominal stress σ_{max}.

5.2.9 Probabilistic Nature of Variables and Parameters of Fracture Mechanics Model

In a manufacturing process the random nature and the inherent variability of the different factors involved, contribute to the stochastic nature of the die life. The probabilistic nature of these variables is well approximated by introducing a factor of variability to each of these variables and the resulting die life distribution can be characterized by a suitable reliability model. A number of variables which contribute to the statistical distribution of the die life are summarized as below;

- The distribution of initial crack.
- The distribution of load and the stress acting on the die surface.
- The distribution of fatigue strength data and fracture toughness of the die material (which is estimated by laboratory experiments).
- Stochastic nature of surface roughness of the die and work material.
- The statistical nature of parameters of work material strength.

In Eq. 5.26 and 5.27. the K_{1c},σ_{max}, m, C, a_i and a_f are all assumed to be normally distributed and identified as X_i with $\mu(x_i)$, $\sigma(x_i)$ representing the respective mean and standard deviation of the random quantity X_i, i = 1,2,3,....N. Now, in order to estimate the cycles encountered by the die before the crack reaches the final crack length of failure, the Eq. 5.26 has to be numerically integrated with the limits a_i and a_f^*. The final crack length a_f^* depends on the fracture toughness K_{1c} of the die material and the crack geometry. The statistical distribution of the final crack depends on the distribution of the maximum nominal stress σ_{max}. The Eq.(5.26) is integrated a number of times, each time the variable being represented by a pre selected variate of a well defined statistical distribution.

Monte Carlo Simulation is a technique used to predict the statistical distribution of the life of a system or device (in this case extrusion dies) and it is considered to be equivalent to the performance of actual experiments, if the data input (values of the parameters) are accurate. The basic procedure involved in the application of the technique is that the fixed initial crack length is pre-determined from a sample of normally distributed initial crack lengths with $F(a_i)$ as the probability distribution and each crack length a_i is then compared with the critical crack length a_f^*. Once the initial crack reaches the critical length which is function of the fracture toughness and maximum flow stress, the die is considered to have failed. By running the simulation a number of times, the life of the dies under the same nominal and process conditions is repeatedly estimated. Later, from the sample of die life generated, the statistical distribution is established and the probability of failure and the reliability of dies are estimated.

The main advantage of this technique is that the stochastic nature of the crack growth can be easily simulated by introducing the relevant statistical distributions for the material properties such as fracture toughness, initial crack length, etc., and the die life can be estimated more accurately. Further, the accuracy of the output is increased by increasing the number of simulations performed.

The statistical distributions for the random variables involved in the model are predetermined each time a simulation is performed. The details regarding the extrusion process and the details of a typical die used in industry are shown in Table 5.3 and Table 5.4. While details relating to the the product and predetermined distributions of the variables for extrusion dies are presented in Table 5.5 and Table 5.6.

5.2.10 Assumptions of the Model

1- An initial crack length of 0.00005m is assumed to be inherent in the die material due to reasons mentioned earlier [42]. Further, the crack length is normally distributed with a mean and a standard deviation.

2- The mean value of fracture toughness and other material parameter values obtained experimentally are true and valid under actual operating conditions, the distribution of K_{1c} is normal.

3- The fracture toughness of the die material is assumed to remain same at working temperature $(400 - 470°C)$ during extrusion.

4- All the material variables, die geometry, etc., and the parameters of the fracture mechanics are normally distributed, where as some of the operational variables such as speed, temperature, etc. may or may not be distributed..

4- The limiting crack length a_f^* was taken to be half the value of a_f (calculated from Eq. 5.27), after analysing a number of failed dies, and consulting with the engineers at ALUPCO.

5.2.11 Monte Carlo Simulation for Life Prediction due to Fatigue Fracture

The effects of the inherent statistical variability of the different variables of the proposed die life prediction model, such as initial crack length, fracture toughness and the flow stress, etc., on the distribution of the die life can be very well approximated by applying the *Monte Carlo Simulation* [44, 33].

In this procedure, a sample of uniformly distributed random number, Z_i are generated using the standard random number generator, which is available in the form of a subroutine in the computer library. Later, these random numbers are transformed to the required statistical distributions by making appropriate statistical fits to the reliability model. Some of the different distributions are presented below.

Table 5.3: Extrusion process details.

Process	Hot forward extrusion
Extrusion pressure	2000/2700psi
Press rated capacity	1630/2500ton
Container dia.	186/224mm
Container temp.	450-460°C
Lubrication	None
Ram velocity	0.005mm/s

Table 5.4: Details of die material.

Die Material	H-13 steel (High chrome)
Composition	C-0.4%, Cr-5%, Si-1%, Mo-1.4%, V-1%
Hardness	46-52 RC
Fracture Toughness	63.5MPa$\sqrt{m}$
Temperature	420-470°C

Table 5.5: Details of product material.

Work material	Ai-6063 Alloy
Composition	Si-0.44%, Fe-0.18%, Cu-0.02%, Mn-0.02%, Mg-0.51, Cr-0.03%, Zn-0.02%, Ti-0.02%, Ot-0.02%
Temperature	470-490°C
Length of billet	750mm
Diameter of billet	178mm
Specific weight	824 gm/m
Typical product thickness	1.3mm

Table 5.6: Distribution of the different variables involved.

Variable	Distribution	Mean Value	Std/Mean
Billet X-sec. Area (do)	Normal	$2.49X10^{-2}m^2$	1%
Product X-sec. Area	Normal	$3.44X10^{-4}m^2$	0.5%
Length of Billet	Normal	$7.5X10^{-1}m$	5%
Strength Coeff. (A)	Normal	37MPa	5%
Hardening Expo. (p)	Normal	$2.14X10^{-1}$	10%
Ram Velocity	Normal	$5.0X10^{-3}m/s$	10%
Extrusion Angle	Constant	45^o	-
Fracture Toughness	Normal	$63.5\text{MPa}\sqrt{m}$	8%
Paris Const. (C)	Constant	$1.12X10^{-12}m/s$	-
Initial Crack Length	Normal	$5.0X10^{-5}m$	10%

For Normal distribution,

$$X(x_i) = \mu(x_i) + \sigma(x_i)Z_i \tag{5.29}$$

where μ is the mean and σ is the standard deviation.

For Log-normal distribution,

$$X_i = exp\,[\mu_l + \sigma_l Z_i] \tag{5.30}$$

where μ_l and σ_l are the mean and standard deviation of the log-normal distribution

For Weibull distribution.

$$X_i = \eta\,[1 - ln(1 - U_i)]^{\frac{1}{\beta}} \tag{5.31}$$

where η is the scale parameter and β is the shape parameter.

For Uniform distribution,

$$X_i = a + (b - a)U_i \tag{5.32}$$

where a and b are the minimum and maximum values.

The actual steps involved in the working of the model involve various intricacies, the main steps are mentioned below:

Step-1 Using the die life model devised earlier, different mechanical properties are evaluated with their variability observed through experiments and data analysis, as well as from the literature where ever possible.

Step-2 The individual distribution of the parameters involved is generated and stored in the memory of the computer code.

Step-3 Numerical integration of the Eq.5.26 is done by using the mechanical properties calculated or established from literature in Step-2, to form an array of cycles to failure N_f.

Step-4 Then, after arranging the cycles to failure N_f, the reliability, failure rate and other statistical parameters are estimated. [using the data analysis technique for grouped data, [29]]

Step-5 Finally the simulated die reliability is compared with the actual observed values devised through the data analysis in ch.4. Other statistical plots are also drawn to verify the importance of the work.

The synthetic data sample coming from the simulation is similar to a sample of actual experimental observations, which can be presented in the form of a histogram or any method of statistical estimation and inference may be used to analyse data.

5.2.12 Comparison of the Simulated Life with Actual Life Data from the Industry

The die life failure data was categorized on the basis of whether failure was due to wear or fracture; majority of the failure were due to these two modes. The transformed fracture data was compared with the simulated life data obtained through fracture mechanics fatigue life simulation model and is shown in Fig. 5.6, 5.7 and 5.8.

A few die sets are selected for representation purpose and to keep the study impartial, three sets are chosen which represent the low, medium and high profile complexities. The dies are classified as least, medium and most complex dies according to the proposed die complexity definitions (Complexity 4) used in chapter 4.

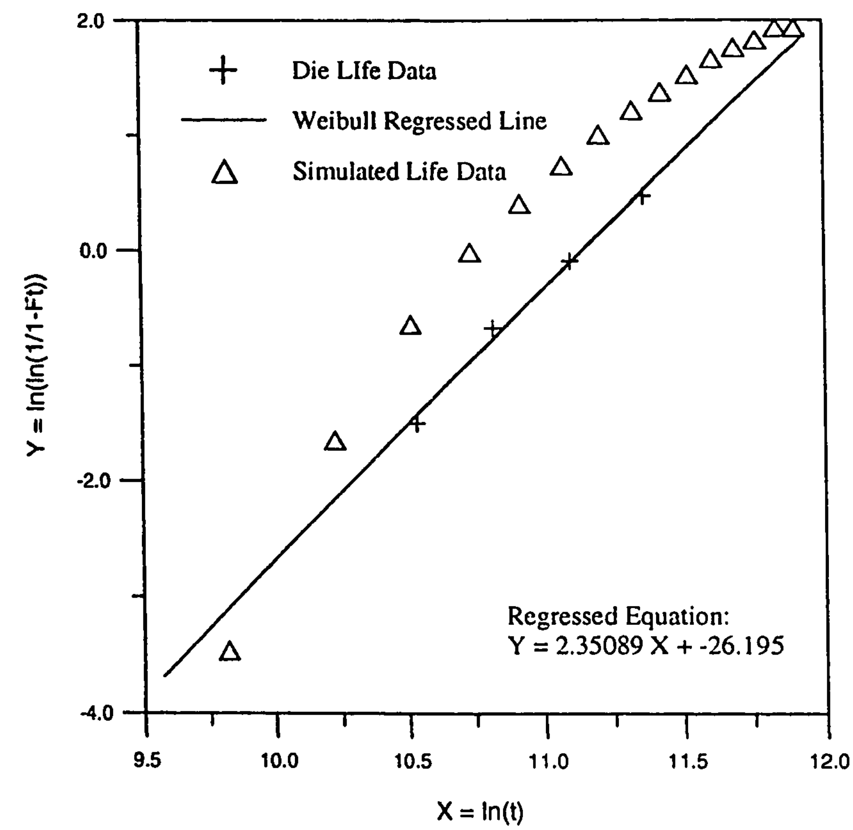


Figure 5.6: Simulated life of least complex H-13 die (Comp.4 = 0.13; Die No. S1113), failed due to fracture, time to failure t is measured in kgs. of metal extruded. [η = 69342.2kg and β = 2.35(fit to the data)][R-sq = 0.9921].

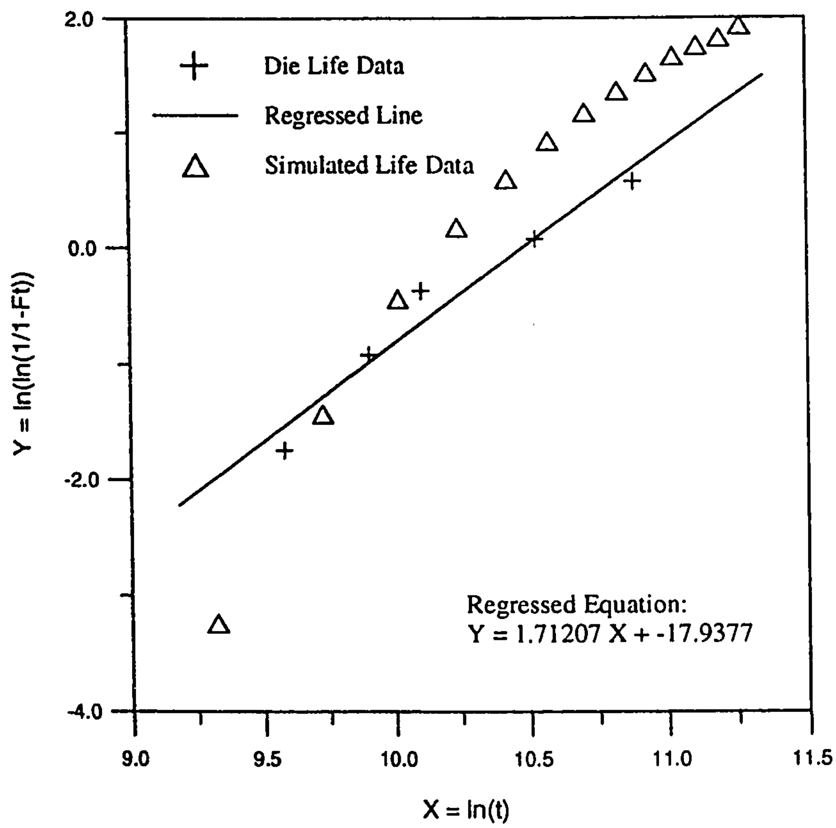


Figure 5.7: Simulated life of medium complex H-13 die (Comp.4 = 0.18; Die No. H9062), failed due to fracture, time to failure t is measured in kgs. of metal extruded. [η = 35512.1kg and β = 1.71(fit to the data)][R-sq = 0.9570].

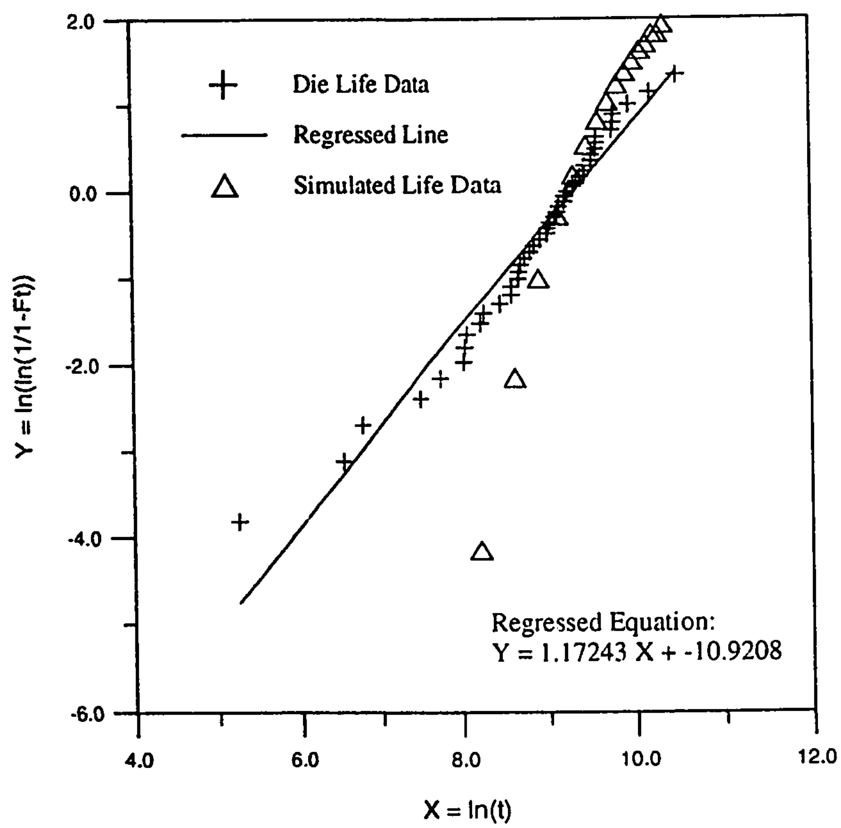


Figure 5.8: Simulated life of most complex H-13 die (Comp.4 = 0.57; Die No. H9028), failed due to fracture, time to failure t is measured in kgs. of metal extruded. [η = 11099.7kg and β = 1.17(fit to the data)][R-sq = 0.9550].

5.3 Simulating die life failed due to wear

The fracture mechanics based fatigue life prediction model devised earlier is only applicable for the dies which fail due to fracture, while dies not only fail due to fracture but also due to other factors such as wear and deflection as was shown earlier(Fig. 3.3). Deflection in many instances can be attributed to excessive wear therefore as an approximation deflection failures will be combined with wear failures. To predict the life of the die failed due to wear another model for wear is proposed.

5.3.1 Wear Theory Based Die Failure Analysis

Prior to extrusion process the die is usually preheated upto 600 to 650^oF (315 to 345^oC), and the billet is preheated upto 750 to 800^oF (400 to 427^oC). The billet surface oxidizes forming aluminum oxide (Al_2O_3) while being subjected to heat. The aluminum oxide forms a rhombohederal crystal which is almost as hard as some of the compounds of diamond, and is extremely abrasive. If the die is preheated in an oxidizing atmosphere, care must be exercised not to allow the die to exceed a temperature of 840^oF (450^oC). At this temperature the die surface will begin to form an iron oxide on the surface of the nitrided case. When this occurs, it will begin to alter the performance of the nitrided case, thus reducing the yield of aluminum extruded through the die. Combination of these two phenomena results in accelerated wear on the bearing surface of the die. The wear can be reduced, if the die can be preheated in a non-oxidizing system either under atmosphere or partial pressure at least. The mechanics of erosion of the bearing face of the nitrided die, commence at the pre-heat stage, if preheating is done in atmosphere or vacuum, oxygen causes pitting and encourages porosity on the nitrided surface. In addition, abrasive characteristics of the aluminum oxide, lead to both premature and catastrophic failure of the bearing surface. Many attempts have been made to reduce the continued problem of erosion and wear on the bearing faces of aluminum extrusion dies. Regardless of the fact that the die configuration is a bridge die. or a hollow die. the die will still be subjected to intensive wear and erosion from aluminum oxide.

From the experimental work documented in literature [45]: It is observed that the wear mechanism of a tool steel die (H-13) when the working material is Aluminum is of the nature;

$$D(t) = A + Bln(t) \tag{5.33}$$

where,

D(t) = depth of wear at time t

A and B are constants, and

t = time in number of kilograms extruded or pushed through the die.

In this analysis, where dies of a variety of shape (complexity) are used, we will assume that above equation represent the growth of the most severe wear zone on the die. D(t) is the largest wear damage on the surface at time t. Eq. 5.33 represent the model devised from a single realization of the wear process. which is the usual deterministic approach. If such wear tests are conducted repeatedly several times we will obtain a spectrum of values following the underlying trend of Eq. 5.33. However the parameters A, B and resulting value of D(t), all will be random in nature, which can be characterized by corresponding bold faced letters:

$$\mathbf{D}(t) = \mathbf{A} + \mathbf{B}ln(t)$$

If scatter in initial wear i.e., $\sigma(\mathbf{A}) = \sigma(D(1))$ is very small (or can be ignored) then $\mathbf{A}$ will behave as a deterministic quantity (i.e., $\mathbf{A} = A$) and corresponding random function of wear damage will be:

$$\mathbf{D}(t) = A + \mathbf{B}ln(t) \tag{5.34}$$

where, $\mathbf{B}$ has an average value $\mu_{\mathbf{B}}$, standard deviation $\sigma_{\mathbf{B}}$ and a modal value $\hat{B}$.

5.3.2 Simulation Model Formulation

It is a well observed fact that a die fails at it's intricate sections where the stress concentration is maximum, excessive erosion of wear occurs in a region of the surface that is in contact with the extruding metal. Hence, it can be concluded that the die failure due to wear is dictated by the probability of the maximum depth of wear eroded from the die surface. Statistically speaking, we can say that the die failure depends on the Extreme Value Distribution of the wear depth. It is imperative to mention that wear itself is Extreme Value Distributed but the time to failure(i.e. time to reach a critical level of wear damage), be weibull distributed as shown below;

The probability of finding the largest wear depth D(t) is given by [29];

$$F(D(t)) = exp(-exp(-\alpha(t)(D(t) - u_{D(t)}))) \tag{5.35}$$

and the expected value of the deepest wear depth is,

$$\mu_{D(t)} = E(D(t)) = u + \frac{\gamma}{\alpha(t)} \tag{5.36}$$

where,

$u = u_{D(t)}$ is the mode of the distribution of the largest wear depth at time t and $\gamma = 0.57721$. Where $\alpha(t)$ is the scatter parameter of the distribution; and is linked to the standard deviation $\sigma(D(t))$ of the deepest wear at time t as follows:

$$\sigma(D(t)) = \frac{\pi}{\sqrt{6}\alpha(t)} \tag{5.37}$$

Since $P[D(t) < D^{*}(t)] = P[T > t] = R(t)$, the reliability based on the critical level of wear $D^{*}(t)$ is given by;

$$R(t) = exp\left\{ -(\frac{t}{\eta})^{\beta} \right\} \tag{5.38}$$

for $D(t) > D^*(t)$

It can be easily shown that [46];

$$\beta = \alpha B \quad (5.39)$$

$$\eta = exp\left\{\frac{D^*(t) - A}{B}\right\} \quad (5.40)$$

$\mathbf{D}(t)$ being extreme value distributed with mean $\mu_{D(t)}$, standard deviation $\sigma_{D(t)}$ and mode $u_{D(t)}$, implies that:

$$\mathbf{B} = \frac{\mathbf{D}(t) - D(1)}{lnt}$$

for any value of t will also be extreme value distributed with mean $\mu_{\mathbf{B}}$, standard deviation $\sigma_{\mathbf{B}}$ and $u_{\mathbf{B}} = \hat{B}$. If we assume that the mode of the random die wear process of Eq. 5.33 has a following characterization where A & $\hat{B}$ depend on the complexity of the die.

$$u_{D(t)} = A + \hat{B}ln(t) \quad (5.41)$$

and the coefficient of variation of the deepest wear pit ν is

$$\nu_{D(t)} = \frac{\sigma_{D(t)}}{\mu_{D(t)}} = \frac{\frac{\pi}{\sqrt{6}*\alpha(t)}}{A + \hat{B}ln(t) + \gamma\frac{1}{\alpha(t)}} \quad (5.42)$$

$$a(t) = \rho(A + \hat{B}ln(t)) \tag{5.43}$$

and as t $\rightarrow \infty, a(t) \cong a$ where,

$$\rho = \frac{\nu}{\frac{\pi}{\sqrt{6}} - \nu\gamma}$$

If the extreme die wear scatter is assumed to stabilize for large value of t, as 0.1(i.e. $\nu = 0.1$), we get $\rho = 8.1644 * 10^{-2}$; the values of A, $\hat{B}$ and asymptotic value of $a \cong a(t \rightarrow \infty)$ corresponding to the different dies used are shown in Table 5.7. Note, each die has different A, $\hat{B}$ and a which depends upon the complexity of the die and reflect the difference in the state of stress on each die.

Substituting the value of $u_{D(t)}$ and $a(t) = a$ from Eq. 5.41 and Eq. 5.43 into Eq. 5.35, we obtain

$$t = exp\left\{\frac{D^*(t)}{\hat{B}[1 - \rho ln[-ln(p)]]} - \frac{A}{\hat{B}}\right\} \tag{5.44}$$

This is the equation for generating the time to failure for an individual die subjected to wear failure, where life is terminated when $D(t)$ reaches $D^*(t)$. The critical wear limit $D^*(t)$ is defined in section 5.3.3, and the values for different dies are given in Table 5.7. For Monte Carlo Simulation 1000 values of p was selected from uniformly distributed random variate between 0 and 1, and corresponding set of t_i values were processed and plotted in Fig. 5.9, 5.10 and 5.11.

5.3.3 Failure Hypothesis

Wear related die life is limited by a limiting wear defined earlier, when wear reaches a critical limit $D^*(t)$ the die is discarded and this terminates the working life of the die. The reason for discarding the die is that the die cavity gets eroded out of the specified tolerance provided by the consumer. Hence we see that the value of $D^*(t)$ is not fixed, it rather depends on the die number (manufacturer's code) which extrudes a particular section i.e., it depends upon the nature of the die. The values $D^*(t)$ vary for different dies and the values for the least, medium and most complex dies selected for simulation are shown in Table 5.7.

The values are based upon the one sided tolerances of the dies. The extruded profile's tolerances are based on the criteria of weight per unit length yield.

5.3.4 Results of die life simulations failed due to wear.

The die which failed due to wear and deflection were characterized by Extreme Value Distribution of wear, which gave times to failure as Weibull distributed when simulations were run. Hence this simulation data was compared with the dies which failed due to wear and the Fig. 5.9, 5.10 and 5.11 show the the results. From the regression plot of the transformed data(Fig. 5.9, 5.10 and 5.11) the values of scale parameter η and shape parameter β are evaluated, for the simulated die life data(failed due to wear alone).

Table 5.7: Table showing the values of $D^*(t)$, A, $\hat{B}$, and α for different dies.

Die No.	S1113	H9062	H9028
Relative Complexity	least	medium	most
$D^*(t)$	$1.5X10^{-4}$	$7.5X10^{-5}$	$7.5X10^{-5}$
A (m)	$2.7337X10^{-4}$	$1.4204X10^{-4}$	$2.3755X10^{-4}$
$\hat{B}$ (m)	$1.1634X10^{-5}$	$7.3060X10^{-6}$	$1.5595X10^{-5}$
α (m^{-1})	$8.1655X10^{4}$	$1.6331X10^{5}$	$1.6331X10^{5}$

5.4 Comprehensive Simulation Model

Two simulation models have been used so far to predict the life of a die failed either by fracture or by wear, but in practice both the mechanisms work together. Hence. a comprehensive simulation model was needed to predict the life of a die irrespective of whether it failed due to wear or fracture.

5.4.1 Competing Risk Model

To formulate an extensive simulation model, competitive risk model approach was applied. The reliability of a die failed due to fracture is given by Eq. 5.45, while the reliability of the die whose primary cause of failure was wear is given by Eq. 5.46.

$$R_f(t) = exp\left\{-(\frac{t}{\eta_f})^{\beta_f}\right\} \tag{5.45}$$

$$R_w(t) = exp\left\{-(\frac{t}{\eta_w})^{\beta_w}\right\} \tag{5.46}$$

The reliability of the die under competing risk model will be given by;

$$R(t) = P\left\{(T_w > t)\bigcap(T_f > t)\right\} \tag{5.47}$$

and if the individual fracture and wear based reliabilities are independent of each other than the resulting reliability is simply the product of the two as shown;

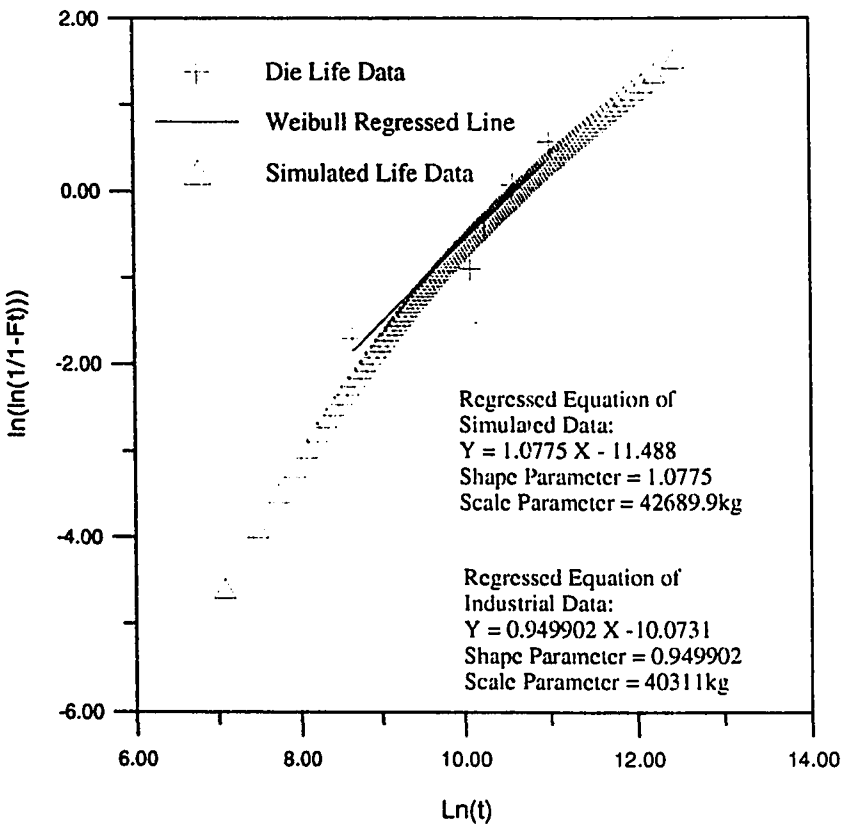


Figure 5.9: Simulated life of least complex H-13 die (Comp.4 = 0.13; Die No. S1113), failed due to wear, time to failure t is measured in kgs. of metal extruded. [R-sq = 0.9234]

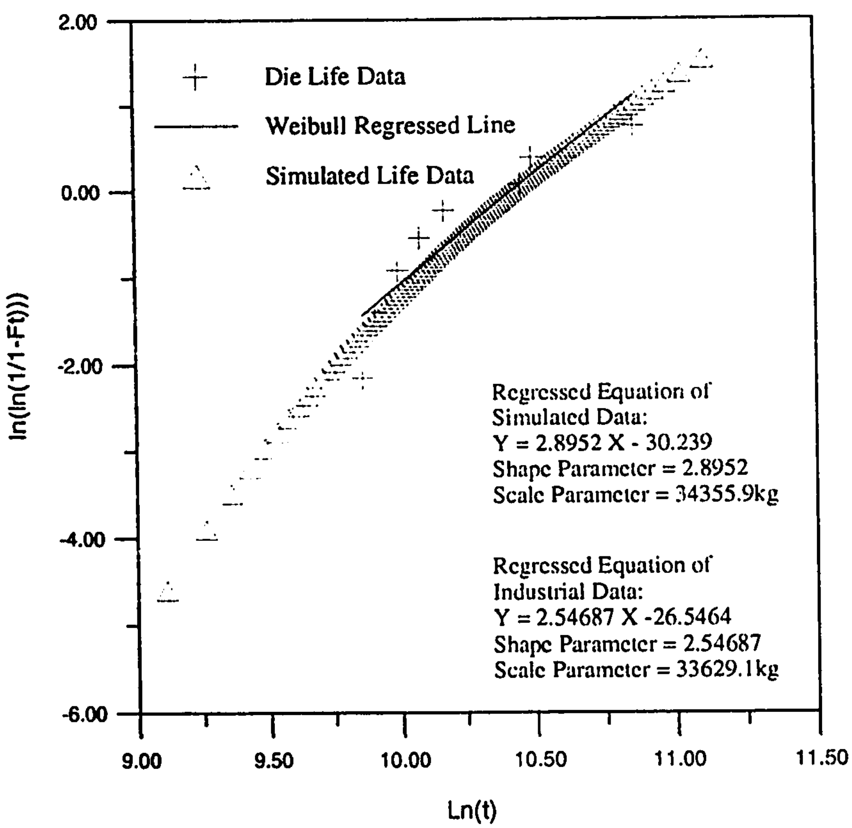


Figure 5.10: Simulated life of medium complex H-13 die (comp.4 = 0.18; Die No. H9062), failed due to wear, time to failure t is measured in kgs. of metal extruded. [R-sq = 0.8437]

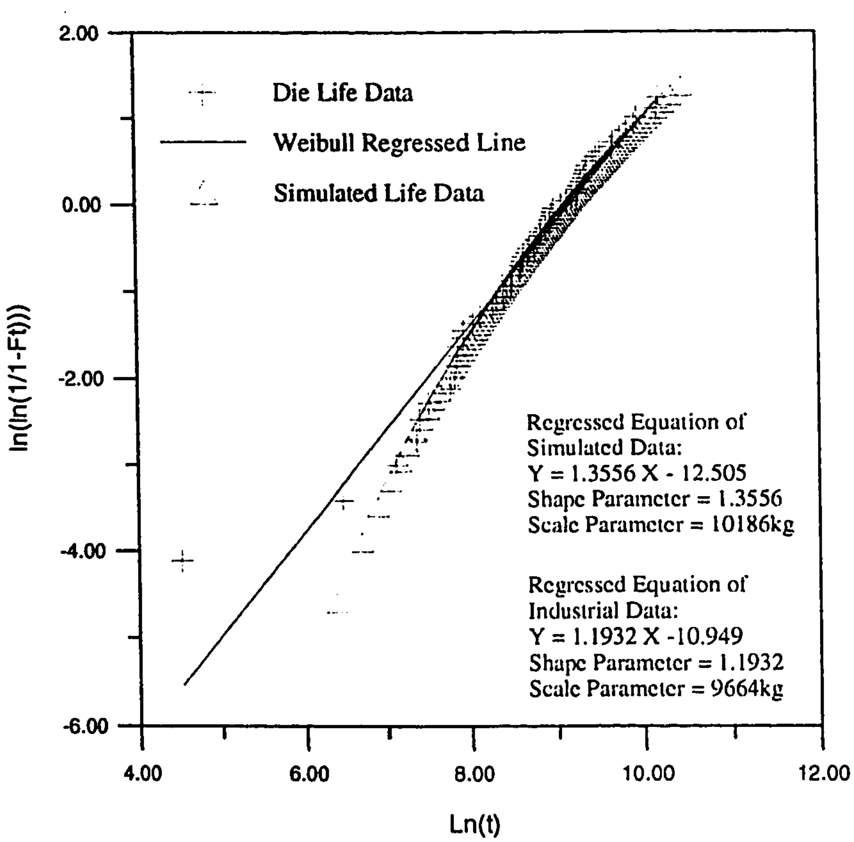


Figure 5.11: Simulated life of most complex H-13 die (comp.4 = 0.57; Die No. h9028), failed due to wear. time to failure t is measured in kgs. of metal extruded. [R-sq = 0.9519]

$$R(t) = P[T_w > t] * P[T_f > t] \tag{5.48}$$

$$R(t) = R_f(t) * R_w(t) \tag{5.49}$$

The distribution of $R(t)$ can be simulated using the following technique. The technique is simple, an array of n simulation runs for both the fracture and wear model is generated in parallel, and the minimum life of the die for the *ith* simulation will generate the time to die failure, t_i.

$$t_i = min(t_f, t_w) \tag{5.50}$$

This is repeated n times for t_f and n times for t_w. Physically speaking, wear and fatigue fracture both worked in parallel to fail the die: the one which reached its respective critical value first is considered to be the reason of failure.The array of simulated times to failure for this comprehensive competitive risk model is compared with the complete die failure data extracted from the industry and a very good agreement was observed. The simulated die life data is checked for Weibull validity by conducting regression analysis on the transformed data as shown in Figures 5.12, 5.13 and 5.14. It is observed that the failure data follow a Weibull distribution. First of all the failure times obtained through the simulation are sorted in an ascending order, then they are bunched into groups, after which the probability functions are derived.The Figures 5.15, 5.16, 5.17, and 5.18, show the comparison of the respective reliability *R(t)* and frequency distributions *f(t)* obtained through the simulation, model and data.

The fracture mechanics fatigue life simulation model devised in this chapter takes good account of the stochastic nature of variables which lead to the ultimate die failures due to fatigue fracture. Similar approach was applied for wear out failures or deflected failures. and it gave good simulation results. Finally. the comprehensive competitive risk model incorporated to the real situation of failure. This approach is promising in that, it gives a life of a particular die through its working parameters, and hence by applying this technique we can forecast the life of a new die in it's design stage.

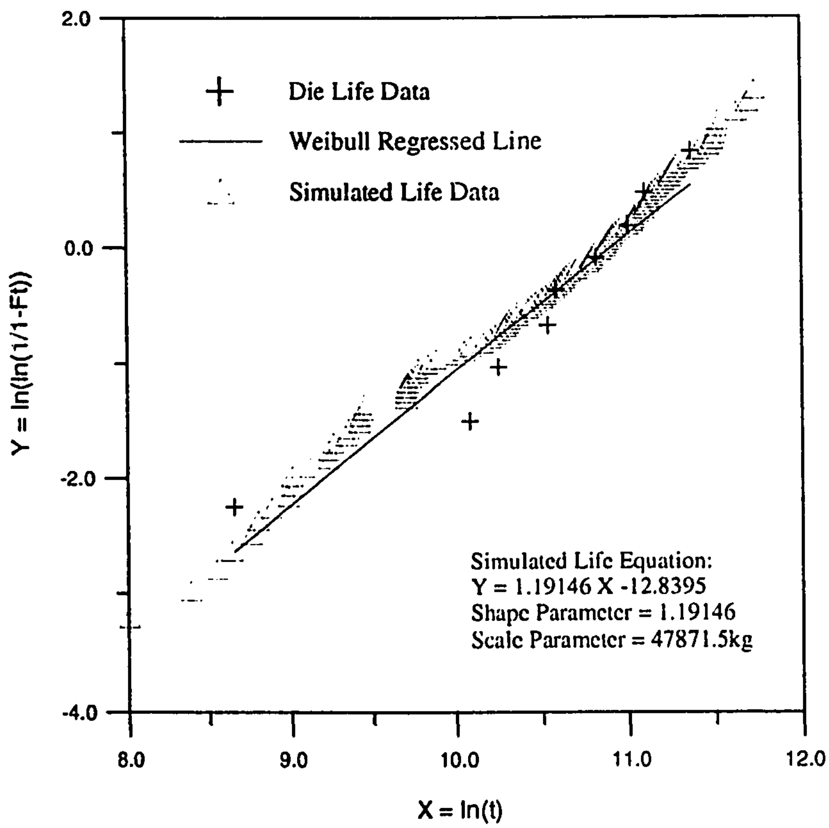


Figure 5.12: Combined Simulated life of the least complex H-13 dies failed due to fracture and wear, time to failure t is measured in kgs. of metal extruded. (Die No. S1113)[R-sq = 0.9067]

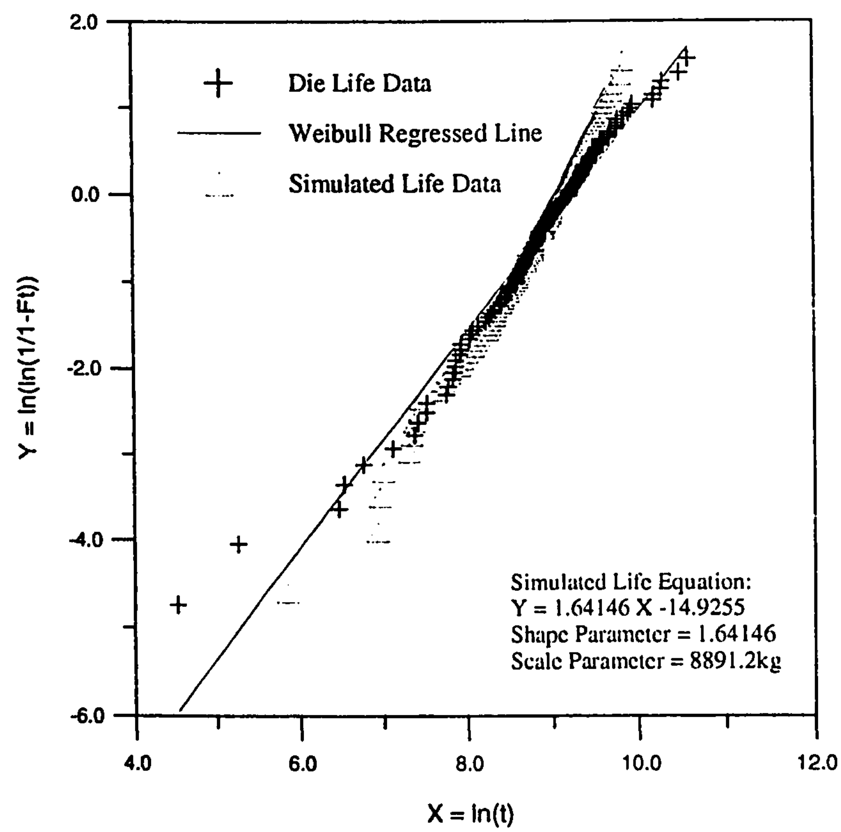


Figure 5.13: Combined Simulated life of the most complex H-13 dies failed due to fracture and wear, time to failure t is measured in kgs. of metal extruded. (Die No. H9028)[R-sq = 0.8987]

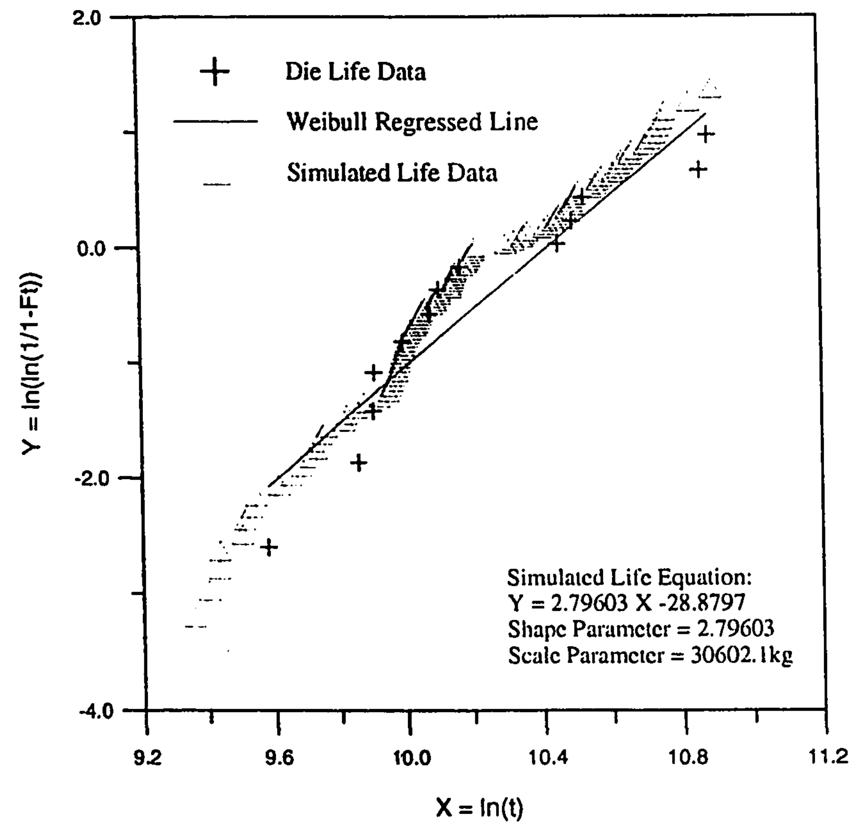


Figure 5.14: Combined Simulated life of the medium complex H-13 dies failed due to fracture and wear, time to failure t is measured in kgs. of metal extruded. (Die No. H9062)[R-sq = 0.9701]

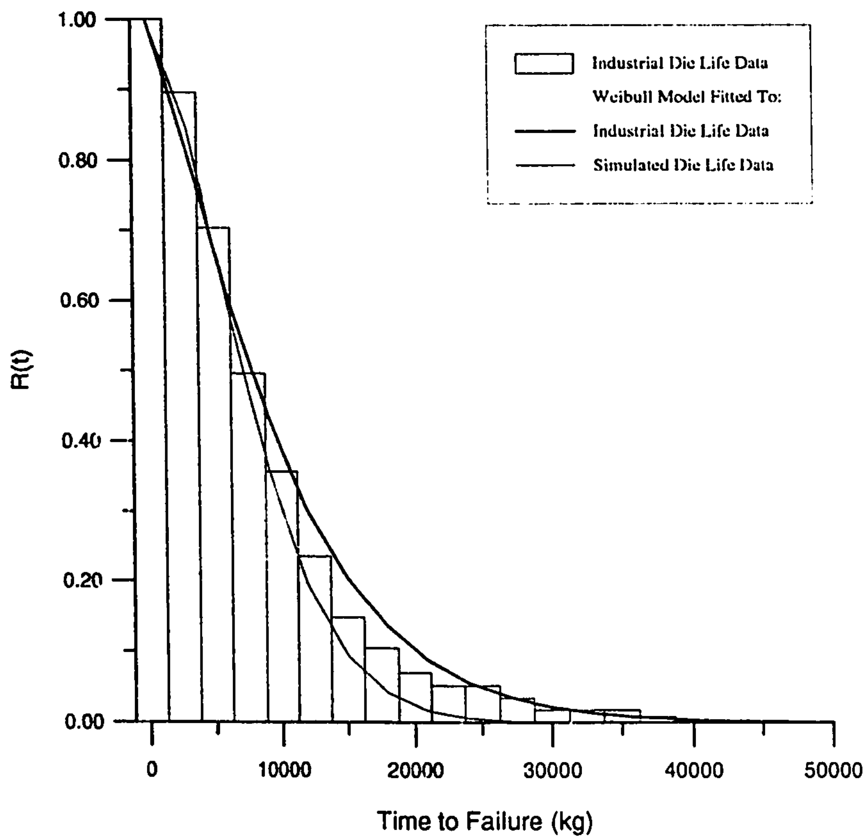


Figure 5.15: Simulated reliability comparison of the most complex H-13 die (Die No. H9028). [η = 10386.2kg and β = 1.26(fit to the data); η = 8891.2kg and β = 1.64(simulation)].

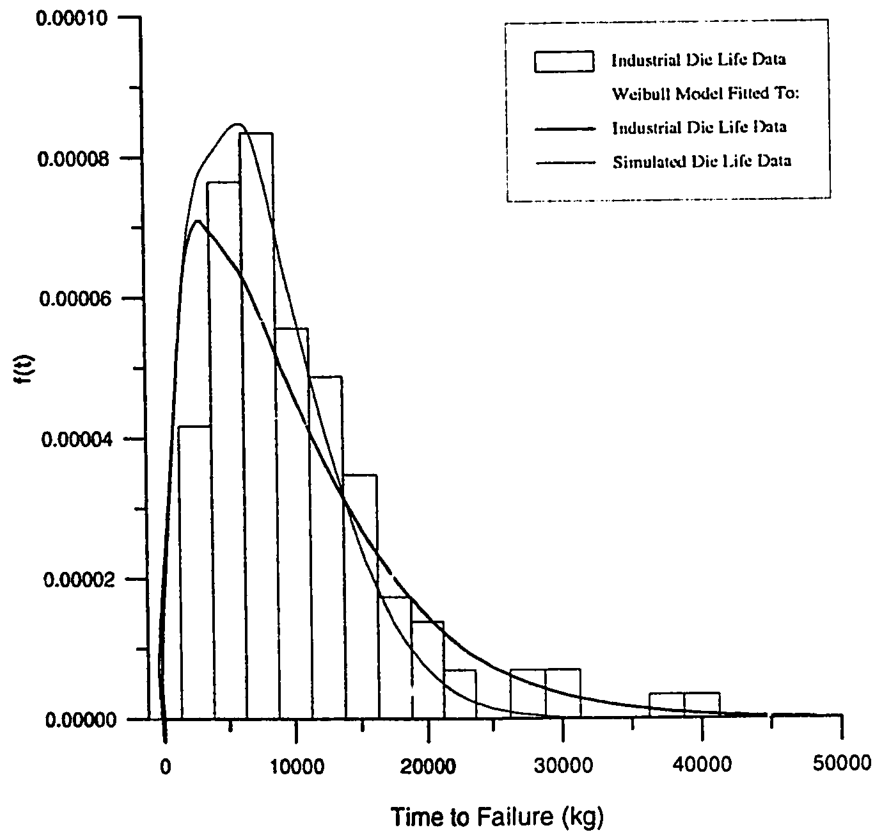


Figure 5.16: Simulated frequency distribution comparison of the most complex H-13 die (Die No. H9028). [η= 10386.2kg and β = 1.26(fit to the data); η = 8891.2kg and β = 1.64(simulation)].

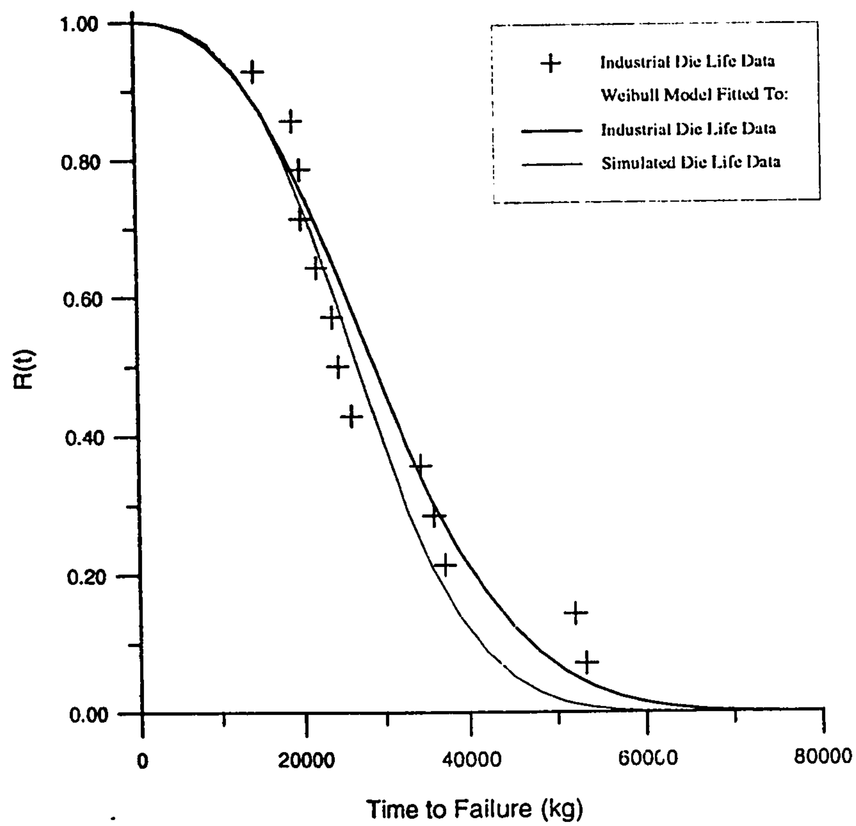


Figure 5.17: Simulated reliability comparison of the medium complex H-13 die (Die No. H9062). [η = 33536.8kg and β = 2.477(fit to the data); η = 30602.1kg and β = 2.79(simulation)].

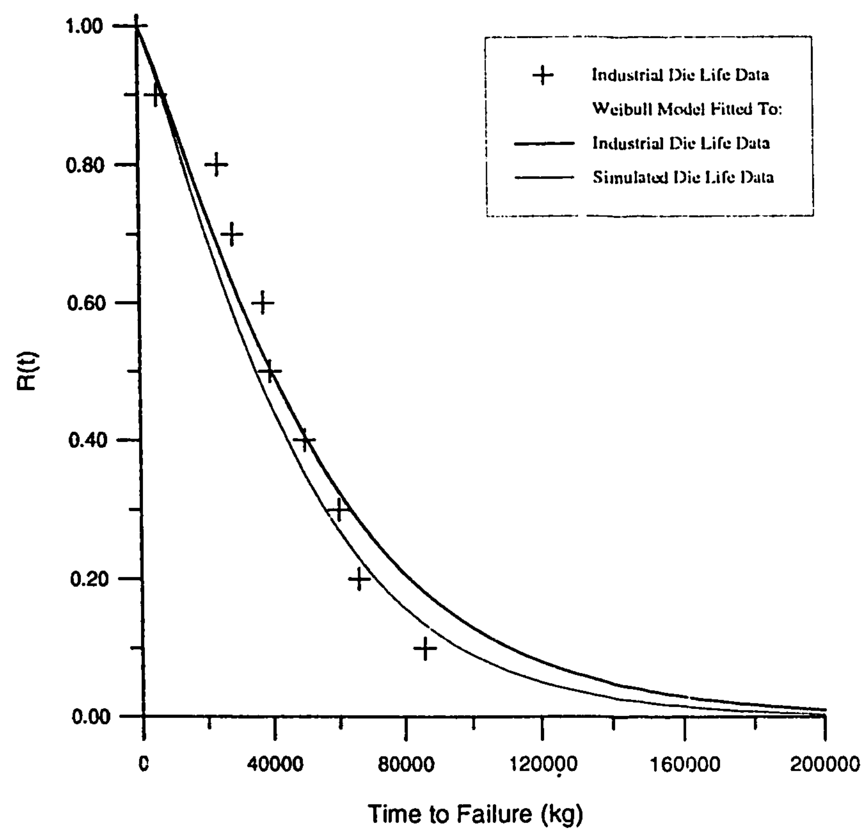


Figure 5.18: Simulated reliability comparison of the least complex H-13 die (Die No. S1113). [η = 54469.7kg and β = 1.173(fit to the data); η = 47871.5kg and β = 1.19(simulation)].

Chapter 6

Die Life Enhancement by Optimal Heat Treatment

The service life of tooling plays an important part in the economics of extrusion. In addition, to the correct material selection, the best material quality is of paramount importance. However, defects in design, manufacture, heat treatment and in operation are frequently revealed by investigation.

The target of various die improvement strategies is to provide an optimal blend of desirable properties to resist fatigue, wear, deflection and deformation simultaneously. After proper design and proper heat treatment, surface hardening is the key to die life enhancement. With a good surface hardening we gain wear resistance, but create a material with reduced fracture toughness. A proper heat treatment will produce an optimal mix of these two competing requirements, i.e. high wear resistance and high fracture toughness. In this chapter, the heat treatment procedure and its certain important aspects are discussed, which play a pivotal role in die life enhancement.

6.1 Surface Hardening

The most widely accepted surface hardening methods are:

- **Carburizing.**
- **Carbonitriding.**
- **Nitriding.**
- **Induction Hardening.**
- **Hard Chrome Plating.**

Amongst the above, carbonitriding and nitriding are the most popular surface hardening techniques used for hardening aluminum extrusion dies in industry. Nitriding is attractive because of higher hardness levels then carburizing with minimal or no distortion after treatment. But it is also cumbersome due to thick brittle white layer which in many instances has to be removed. Another obstacle is that nitriding, a historically newer development than carburizing, has always been compared to it without recognition of substantial differences between the two. Such misguided approach has precipitated demands for case depths similar to ones normally associated with carburizing. It is obvious that such case depths require extremely long processing times rendering the whole process impractical in many applications.

6.1.1 Nitriding Process

Nitriding is a very complicated process influenced by a number of variables that are dependent on specific phenomenon taking place at the gas/metal interface. These phenomena, in turn, are influenced by the chemical or physical condition of the component's surface, such as degree of passivation, roughness, etc. The most significant factor in achieving satisfactory process control appears to be the formulation of basic thermodynamical relations at the gas/metal interface during breakup of the atmosphere's component. The exact nature of these reactions (i.e. mass transport of the gaseous phase formation) is determined by the kinetics of the process.

The breakup of ammonia and the subsequent diffusion of nascent substrates in to the iron matrix follows the mechanism shown in Fig. 6.1.

The diffusion process involves a series of steps [47]:

- Transport of NH_3 molecules in to the transient zone immediately adjacent to the component surface.
- Diffusion of NH_3 molecules through the zone.
- Adsorption of NH_3 molecules.

- Catalytic breakup of NH_3 molecule in to NH_2, NH, N and H.
- Transport of recombined nitrogen and hydrogen molecules through the transient area.
- Transport of absorbed nascent nitrogen in to iron.
- Diffusion of nitrogen in to iron depending on local nitrogen concentration profiles.
- Localized nuclei formation of γ' or ϵ nitrides on the surface after maximum nitrogen concentration in α iron has been exceeded.
- Growth of nitride nuclei in the direction perpendicular and parallel to the surface.
- Formation and growth of the γ' phase.
- Formation and growth of the ϵ phase.
- Increase in thickness of the superficial layer consisting of γ' and/or ϵ nitrides.
- Diffusion of nitrogen from the iron nitride-α iron phase interface in to iron substrate.

It is interesting to note that the principal alloying element in nitriding, carbon can influence the properties of the superficial layer. The analysis of a triple Fe-C-N diagram shows that carbon is soluble to various degrees in both phases. At 550^oC,

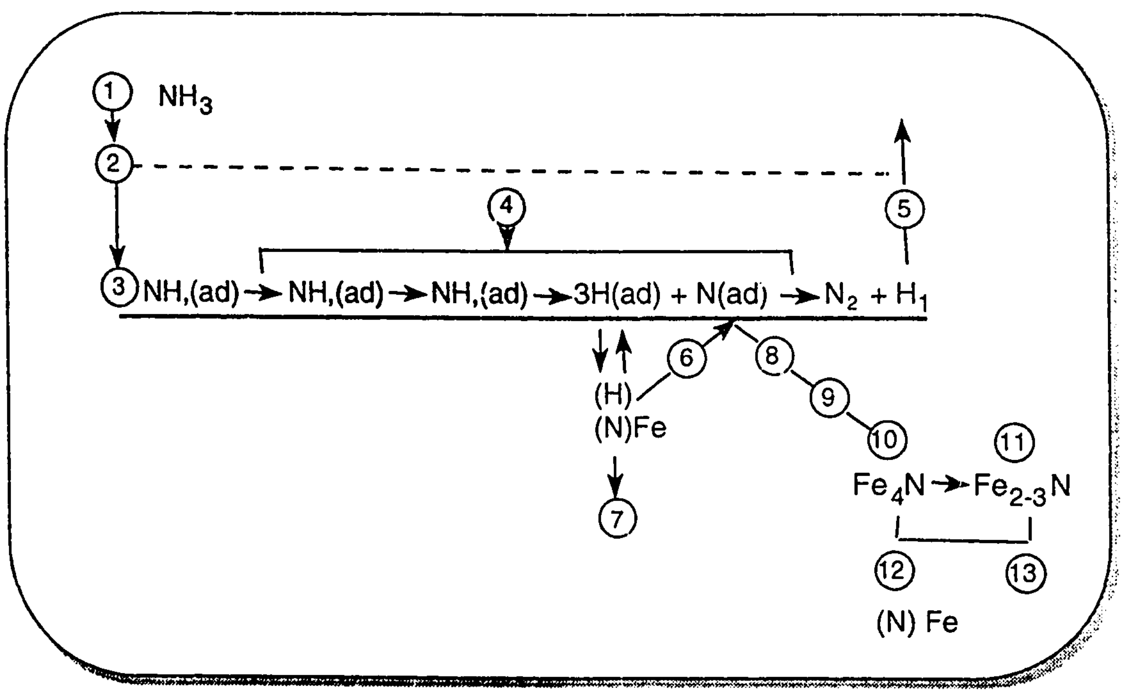


Figure 6.1: Schematic representation of a diffusion process occurring during nitriding.

the solubility of carbon in γ' is 0.2% and in ϵ upto 3.8% whereas total concentration of carbon and nitrogen in ϵ does not exceed 11.3% by weight. Both phases, therefore to a lesser or greater extent, contain various levels of carbon and nitrogen which in turn strongly effects their properties.

6.1.2 ALUPCO Nitriding Diagram

In ALUPCO, nitriding is used with a cycle time of approximately 10hrs as shown in Fig. 6.2. The concentrations and flow rates of individual components of nitriding are mentioned below along with the time to temperature diagram.

Concentration.	**Flow rate.**
$NH_3 = 99.99\%$	250 Lt/hr(0.25m^3/hr)
$N_2 = 99.5\%$	250 Lt/hr(0.25m^3/hr)
$CO_2 = 98.0\%$	15-20 Lt/hr(0.015-0.02m^3/hr)

Ion nitriding using the pulsed plasma technique is the process which offers the aluminum industry the option of controlling the die case to create the optimum metallurgy suitable for both die and press [18]. It is a process which has gained wide acceptance in Europe, Eastern Europe and Far East, because of its consistency of results, controllability of metallurgy, reduced press down time, reduced die correction and improved through-put. All of these aspects can not only improve the aluminum

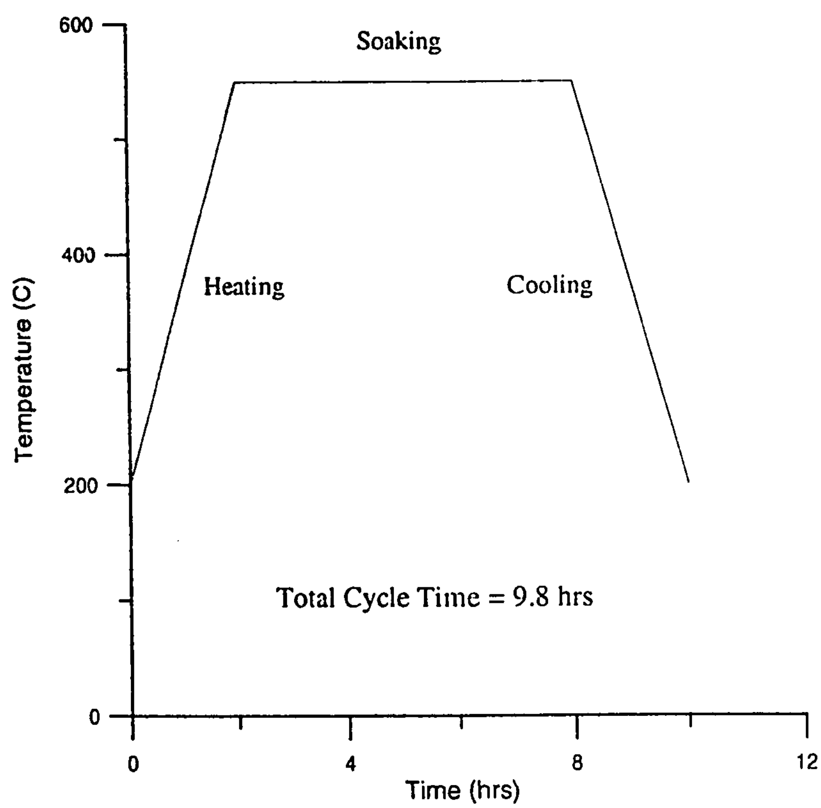


Figure 6.2: Time to temperature diagram used for nitriding in ALUPCO.

industry's return on assets invested, but will improve their overall profitability and efficiency in a competitive international environment.

Nitriding results in a hard surface layer which is very resistant to wear and erosion. The nitrided layer is, however, brittle and may crack or spall when exposed to mechanical or thermal shock, the risk increasing with layer thickness. Before nitriding, the tool should be hardened, and tempered at a temperature at least 90^oF (50^oC) above the nitriding temperature.

Nitriding in ammonia gas at 975^oF (525^oC) or ion nitriding in a 90% hydrogen - 10% nitrogen mixture at 895^oF (480^oC) both result in a surface hardness of 1000-1250 HV [48].

Fig. 6.3 shows that a maximum of hardness is correlated with a minimum of fracture toughness. Therefore it may be favorable to use a steel with reduced hardness for obtaining improved fracture toughness [42]. With the use of this figure, an optimal tempering temperature can be determined, to yield a certain hardness and fracture toughness. This will certainly enhance the reliability of a die.

Thus, the surface of an aluminum extrusion die should be nitrided to such an extent, so as to give it a good wear resistance against hard aluminum oxide but it should not be over hardened, making the bearing surface vulnerable to brittle fracture. The key to die life enhancement is an appropriate nitriding procedure, because as the hardness increases the fracture toughness decreases and lower fracture toughness will make the die fail due to fatigue.

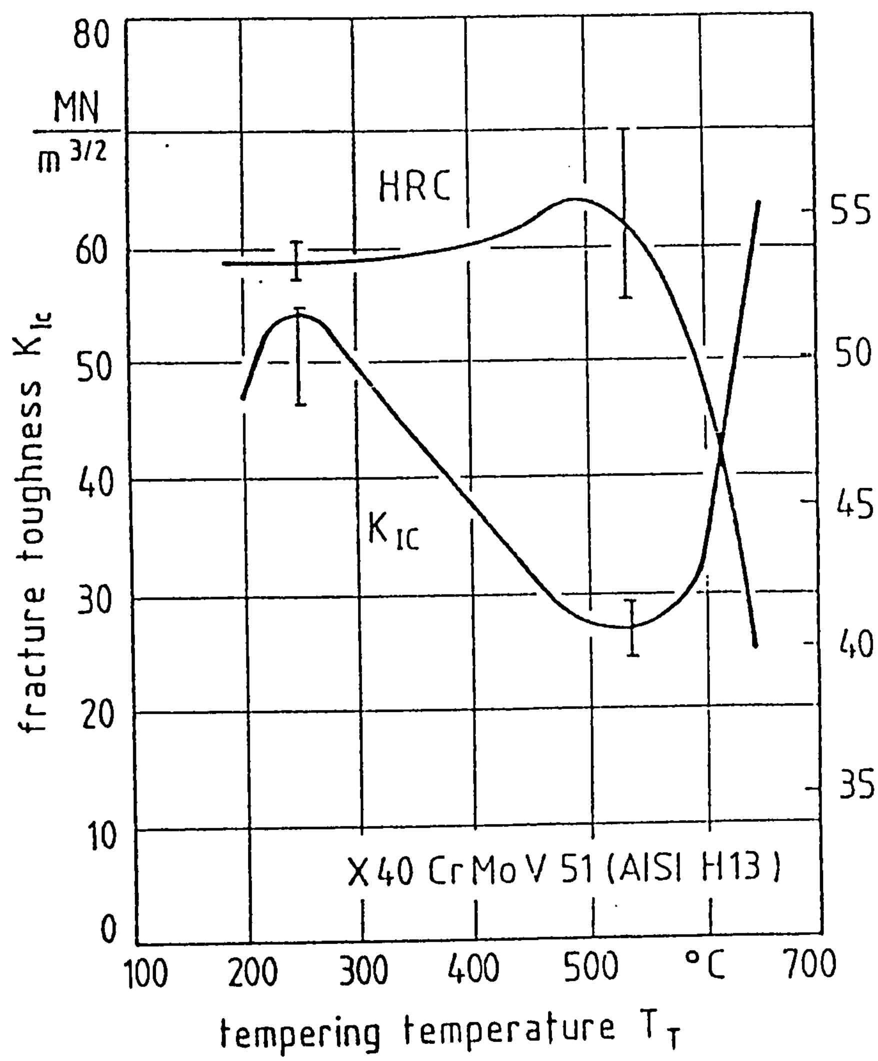


Figure 6.3: Effect of tempering temperature on hardness and fracture toughness of H-13 tool steel [42].

Chapter 7

Conclusions

1. The historical die life data of over 1400 dies was statistically analysed, to establish the appropriate probability distribution characterizing the die life. The times to failure for each set of dies were analysed separately. Weibull distribution was found to adequately represent extrusion die life. The Weibull distribution is, in general, two parameter distribution comprising of a scale parameter η and a shape parameter β, which depict the average life and scatter in the die life. In a few cases, a three parameter Weibull distribution fitted the die life data properly.

2. The extensive data and related information obtained from the industry was organized in terms of profile complexity of the die cavity shape. The complexity factors defined in literature were used to quantify the die complexity. Using the rationale that as the complexity factor increases the average life must

decrease, various complexity factors were plotted against the average life. A general trend of the similar nature was observed for two out of the three cases; however, only *Form Factor* provided relatively better correlation.To search for a better characterization of the complexity, an exploratory study was undertaken, observing the behavior of average life and scatter as a function of the key variables and process parameters. The objective of the study was to provide a predictive regression model for average life in terms of these variables and process parameters. Using this model a refined and more accurate die complexity factor (Complexity 5) is proposed. It is a more comprehensive complexity definition incorporating die life parameters. Hence in the absence of any die life information and having the knowledge of the life parameters, one can predict the die life using either the regression model approach or through the correlation of the complexity factor and the Weibull parameters. Such a prediction will be adequately valid for the plant and operating conditions under consideration.

3. This statistical study presented in chapter 4, represented the die life under all modes of failures i.e., fracture. wear and deflection. The dominating modes of failure are fatigue fracture and wear. Using these modes of failure, simulation models were developed on the fracture mechanics and wear theory basis. The die life criteria was based on critical crack size or critical depth of wear.

Critical crack size and the critical wear depth for the fracture mechanics and wear models respectively were established after consulting with the responsible personnel incharge in the extrusion plant (ALUPCO). The input parameters to the models were either found experimentally or deduced from the literature where ever possible. The Monte Carlo Simulation was conducted separately for the fracture based model and the wear based model and comparison of the individual representative die set (least, medium and most complex) was made. The results were compared by selecting only the relevant data matrix i.e., separately considering dies failed due to fracture or wear, the comparison of the reliability of the representative dies with the industrial data were in good agreement.

4. Since in reality the die failure occurs both due to fracture and wear processes acting in parallel, a comprehensive competitive risk model was proposed to predict the life of the die based on both fracture and wear together. The underlying principle in this model is that both the failure modes work in parallel and which ever of these reaches the respective critical value first terminates the working life of the die. The comparison of the simulation results for this combined comprehensive model presented a very good agreement with the industrial life data of the dies and simulated life is shown to be weibull distributed. These simulated predictions are independent of the plant working

conditions.

5. Finally, the extrusion die life enhancement is proposed by providing an optimal surface nitrided procedure, based on information obtained from literature and personal discussion with the engineering staff in ALUPCO. Tempering temperature plays a vital role, its implications on fracture toughness and surface hardness are also explored, and recommendations are made to arrive at optimal mix of heat treatment conditions. The recommended strategy is to live with relatively reduce hardness of the die, to enhance its fracture toughness.

Thus as an out come of this work, in the absence of any historical die life data, the die reliability can be predicted using either (a) complexity factor correlation, (b) regression or (c) simulation. In addition, it will be possible to calculate the number of dies required to meet a production target, to make a comparative assessments of dies, as well as to determine the age replacement strategies for the die.

7.1 Recommendations for Future Work

The work done in this thesis provides a basis to integrate it in development of rational die maintenance strategies. As an extension of this work the replacement schedule for the dies can be worked out to optimize the life of the die. The work done in this thesis can act as a basis for the comparative assessment of the dies received from different suppliers or manufactured from different materials. Extrusion press variability causing changes in die life can also be studied using the approach used in the work. Also using the extensive data matrix, an expert system can be devised for the maintenance and determination of replacement intervals of extrusion dies.

Through the parameters of the functions which are evaluated and also predicted with a reasonable confidence, optimal die maintenance and replacement cycle period can be estimated accurately. Similar strategies can be applied to different machine tool elements which are exposed to wear out failures, like forging dies, hammers, etc.

Bibliography

[1] Hot extrusion. *Metals handbook 9th ed. Vol 2.* Prentice Hall.

[2] Forming and forging. *Metals handbook 9th ed. Vol 14.* Prentice Hall.

[3] Die steels and components for extrusion, assab. *Industrial brochure.*

[4] A. Czelusniak and Nitrex Metal Inc. Korwin. M.J. Economics of nitreg process use in nitriding of aluminum extrusion dies. *Industrial brochure.*

[5] L.G. Wager and M.M. Barash. Study for distributions of life of hss tools. *ASME. Journal of engineering for industry*, 73(4):225–229, Nov. 1971.

[6] A.L. Kendall and A.K. Sheikh. Coefficient of variation: An index of tool reliability and its significance in automated production. *ASME. Transactions*, pages 362–369, 1976.

[7] A.L. Kendall and A.K. Sheikh. Guidelines for the application of probabilistic models in the replacement polices. *ASME. Transactions*, pages 124–132, 1979.

[8] Sampath W.S. Lee, Y.M. and M.C. Shaw. Tool fracture probability under steady state cutting conditions. *Journal of engineering for industry.*, 100(2):161–167, May, 1984.

[9] Koren Y. Levi, R. and S. Malkin. Probabilistic model for cutting tool fracture control. *Transactions ASME. Journal of engineering for industry.*, pages 263–265.

[10] A.L. Kendall and A.K. Sheikh. Guidelines for the probability models in tool replacement polices. *8th NAMRC*, pages 271–276, 1980.

[11] A.K. Sheikh. Reliability of cutting tools, towards improved performance of tool materials. *The metal society. London.*, pages 195–204, 1982.

[12] H.P. Wirsching and K. Oritz. Fracture mechanics fatigue model in a reliability format. *Proceedings of the 6th international symposium, offshore mechanics and arctic engineering (OMAE). Houston. Texas.*, pages 331–337, Mar, 1982.

[13] W. Reiss. Tool life in solid forward extrusion. *Annals of the CIRP*, 36(1):155–160, 1987.

[14] Metals handbook 10th ed. *Selection of materials for hot extrusion tooling.* Prentice Hall.

[15] Beeley P.R. Tittagala, S.R. and A.N. Bramley. Wear test for hot working die steels. *Metal technology*, 9:434–439, Nov, 1982.

[16] R. Gonzales. User experience with fluidized-bed nitriding and nitrocarburizing of extrusion dies. *Aluminum 2000, 2nd international congress of aluminum, Conference proceedings*, II:207–217, 1993.

[17] A.B. Mew and D.M.M. Guyoncourt. The evaluation of some surface treatments for aluminum extrsion dies. *Aluminum 2000, 2nd international congress of aluminum. Conference proceedings*, II:233–243, 1993.

[18] P. David. Plasma nitriding, an alternative nitriding method for aluminum extrusion dies. *Aluminum 2000. 2nd international congress of aluminum. Conference proceedings*, II:265–273, 1993.

[19] J. Wallbank and V.B. Phadke. Some metallurgical aspects of die failure. *Metal technology*, 9:405–412, Oct, 1982.

[20] G.W. Dion. The contribution of die to surface quality. *Light metal age*, 46(5):30–34, Jun, 1988.

[21] M.P. Clode and T. Sheppard. Formation of die lines during the extrusion of aa-6063. *Materials science and technology*, 6(8):755–763, Aug, 1990.

[22] Annon. Solid extrusion die correction-part i. *Light metal age*, 43(11):5–10, Dec, 1985.

[23] Annon. Solid extrusion die correction-part iii, handling and maintenance of extrusion dies and tools. *Light metal age*, 44(3):10–13, 1986.

[24] Norstrom L.A. Jonson, L. and O. Sandberg. A new precipitation hardening steel for aluminum extrusion dies. *Aluminum 2000. 2nd international congress of aluminum, Conference proceedings*, II:253–256, 1993.

[25] Failure analysis, prevention, Failure of tools, and dies. *Metals handbook 9th ed.* Prentice Hall.

[26] W.A. Kortmann. Failure in extrusion tooling, causes and methods of avoiding failures. *Aluminum 2000. 2nd international congress of aluminum. Conference proceedings*, II:219–231, 1993.

[27] *Metal Working.* ASM, Metals park, Ohio., 1982.

[28] R. Viswanathan. *Damage mechanics and life assessment of high temperature components.* ASM. Metals park, Ohio., 1989.

[29] E.E. Lewis. *Introduction to reliability engineering.* John Wiley & sons, 1987.

[30] H.F. Martz and R.A. Waller. *Bayesian reliability analysis.* John wiley & sons, 1982.

[31] P.D.T. O'Conner. *Practical reliability engineering.* John wiley & sons, 1981.

[32] Laue. K. and H. Stenger. *Extrusion processes and tooling.* ASM, Metals park, Ohio., 1982.

[33] Trong T.Y. Wirsching, H.P. and W.S. Martin. Advanced fatigue reliability analysis. *International journal of fatigue*, 13(5):389–394, Sept 1991.

[34] Personal discussion with the technical staff managing and maintaining the extrusion plant in alupco (dammam).

[35] J.W. Provan. *Probability fracture mechanics and reliability.* Martinus Nijhoff publishers. 1987.

[36] *Cases histories involving fatigue and fracture mechanics.* ASTM Special technical publication:918, 1986.

[37] Kalpakjian. S. *Manufacturing processes for engineering materials.* Addison-wesley publishing co., 1984.

[38] A.J. Schey. *Introduction to manufacturing processes.* McGraw Hill, 1987.

[39] A. Ghosh and K.A. Malik. *Manufacturing science.* John wiley & sons, 1986.

[40] N.C. Pandya and C.S. Shah. *Cylinders. tanks and pipes. 9th revised Ed.* Charotar publishing house, 1993.

[41] R. T. Ault G. M. Wald and R. B. bertola. Development of an improved ultrhigh strength steel for forged aircraft components. *AFML TR 71271 Airforce materials laboratory. Wright-Patterson Airforce Base. OH.*

[42] Klaus Pohlandt. *Materials Testing for the Metal forming Industry.* Spriger-Verlag. 1989.

[43] E.G. Dieter. *Mechanical metallurgy.* McGraw Hill, 1988.

[44] H.P. Wirsching and K. Ortiz. Fracture mechanics fatigue model in a reliability format. *Proc. 6th int. symposium offshore mechanics and arctic engineering (OMAE).Houston.Texas.*, pages 331-337, March 1987.

[45] Elsevier Sequota S. A. *Wear a celebration volume. printed from Wear. vol 100 Dec 1984.* Lausanne and New York.

[46] Anwar Khalil Sheikh and M. Younas. Statistical characterization of pitting corrosion process and life prediction. *Paper presented in the 4th international symposium on advanced materials Islamabad*, sept 1995.

[47] A. Czelusniak and M. Korwin. Advanced surface hardening technologies for steel through nitrogen implantation. *Industrial brochure.*

[48] D. Pye. Ion nitriding of aluminum extrusion dies using the pulsed plasma technique. *Light metal age*, pages 65-67, Aug 1992.

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